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Baseline Characterization and Emissions Control Technology Assessment of HD Gasoline Engines

Southwest Research Inst, San Antonio, Tex

Prepared for

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BASELINE CHARACTERIZATION AND EMISSIONS CONTROL TECHNOLOGY ASSESSMENT OF HD GASOLINE ENGINES

by
Karl J. Springer

FINAL REPORT
Contract EHS 70-110

Prepared for
Environmental Protection Agency
Office of Air Programs
Mobile Source Pollution Control Program

November 1972

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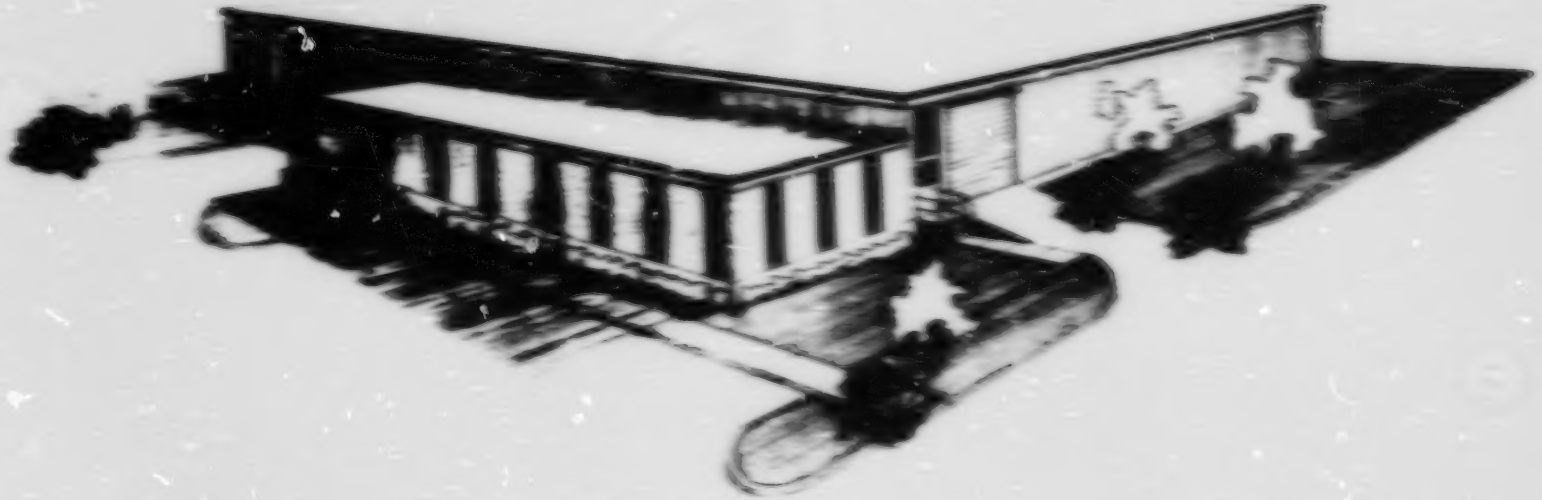

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FOREWORD

This project was initiated by the Characterization and Control Development Branch, Division of Emission Control Technology, Environmental Protection Agency, 2565 Plymouth Road, Ann Arbor, Michigan 48105. The engineering effort on which this report is based was accomplished by Southwest Research Institute, 8500 Culebra Road, San Antonio, Texas, under contract number EHS 70-110. The author, Mr. Karl J. Springer, was the Project Leader of the research and development work. This project, authorized by Modification No. 1 to EHS 70-110, began on March 1, 1972, and was completed November 10, 1972.

The principal engineers associated with this project were Mr. Robert McFarland, who assisted with baseline data and Mr. Clifford D. Tyree, responsible for laboratory control technology evaluation.

The Project Officer cognisant of this project was Mr. John J. McFadden of the Characterization and Control Development Branch, Division of Emission Control Technology, Environmental Protection Agency, 2565 Plymouth Road, Ann Arbor, Michigan 48105. This project was identified within Southwest Research Institute as No. 11-2877-01.

ABSTRACT

Six 1973 spark-ignited gasoline engines, used in trucks above 6,000 lbs. gross vehicle weight, were subjected to baseline exhaust emissions tests. Two groups of three engines, representing various cylinder configurations and displacements were tested by the current 1973 Federal test procedure, a nine-mode constant speed engine dynamometer test method. The concentrations were then converted to mass emissions for the nine-mode schedule using the 1974 Federal Test Procedure applicable to heavy-duty gasoline engines. Each engine was also tested by an experimental three-speed and multi-load schedule with expressions of emissions on a grams per bhp-hour basis. The emissions of interest were unburned hydrocarbons, oxides of nitrogen, carbon monoxide and aldehydes. One popularly used V-8 engine from each manufacturer's group was subjected to a limited series of laboratory tests to demonstrate control device effectiveness. This part of the study was restricted to the use of light-duty items or laboratory-type approaches because of the apparent lack of technology for gasoline engines in heavy-duty service. The experimental multi-modal test procedure was employed to evaluate various control strategies such as basic spark timing, carburetion (air-fuel ratio), air injection, exhaust gas recirculation and an oxidation catalyst singly and in combination. Substantial reductions in all emissions were effected on both engines with a combination of exhaust gas recirculation, air injection and an oxidation catalyst with some increase in fuel consumption and loss in maximum power.

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I. INTRODUCTION

According to statistical information[1]*, all trucks in 1970 comprised about 17 percent (18,747,781) of the total vehicles registered and burn approximately 28 percent of the gasoline consumed in the United States. From sales data[1], approximately 44 percent of the trucks and buses sold in 1970 were above 6,000-lb gross vehicle weight (GVW). This estimate includes diesel vehicles which are a relatively small number.

The Environmental Protection Agency (EPA) has sponsored two programs, one at the Bureau of Mines under Inter Agency Agreement 0139 and the other at Southwest Research Institute to characterize baseline emissions from 15 heavy duty vehicle engine candidates and investigate the effectiveness of control technology. The effort described in this report by SwRI includes six (6) HDV engines supplied by two of the seven manufacturers who cooperated in the overall effort. The engine selection rationale considered engines with low emission levels, distribution of the application range greater than 6,000-lb gross vehicle weight (GVW), high annual sales volume, diversified combustion chamber designs and availability of advanced emission control devices.

A. Previous Projects

Southwest Research Institute's Emissions Research Laboratory has conducted a considerable amount of research with HDVs beginning in June 1967. Past efforts included acquisition of baseline emissions data from 150 gasoline and LPG fueled spark-ignited engine-powered trucks and buses using three experimental road-like chassis dynamometer procedures. To acquire the emissions, a special truck version of the constant volume sampler (CVS) was used, which permitted expression of contuminants on a mass basis. The results of the survey are contained in the SwRI final report[2] which concluded that the three proposed experimental variable-speed cycles were not recommended for use in testing emissions from heavy-duty vehicles powered by spark-ignited engines. The findings of these earlier studies were summarized in AIChE and SAE papers[3, 4] which described the preparations and baseline data results, respectively.

The second major work in this program compared hydrocarbon (HC), carbon monoxide (CO), and nitric oxide (NO) emissions while driving in traffic to chassis dynamometer emissions by the Federal nine-mode constant speed cycle (FTP) for six trucks of various sizes and makes. Using a CVS, the current Federal cycle was submitted to a number of modifications to investigate what improvements might be made to make the Federal procedure agree more with road operation[5].

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*Superscript numbers in parentheses refer to the List of References at the end of this report.

The third in this series of projects, sponsored by the Environmental Protection Agency, was completed in April, 1972. The first of the three-phase project was a broad emission characterization study of four 1959 trucks under a wide variety of engine speeds and power levels. Emission rates of hydrocarbons, carbon monoxide, and nitric oxide were expressed in mass units of grams per minute, per pound of fuel and per bhp-hr. In addition to the steady-state emission maps, a number of transient accelerations and decelerations were studied using a variety of simulated vehicle inertias. The second phase was a four-vehicle study of the effect of four different road routes on emission rates. The road routes were sufficiently different to be distinct, yet were considered representative of actual truck driving. The three phases of this project generated a large body of data that is summarized in the report[6] and included in some detail in a number of appendixes.

The precedent for the operation of gasoline engines on a 23-mode test procedure, with raw exhaust emission measurements expressed on a mass basis, was established in the project completed in April 1972[6]. This present effort utilizes the equipment, instrumentation, and general test approach of the earlier project.

B. Assistance by the Manufacturer

Several meetings were held, beginning in January 1972, with representatives of two H.D. engine manufacturers involved in the SwRI studies. In attendance at these meetings were Mr. John J. McFadden and Dr. Jose Louis Bascunana representing the EPA and Mr. Karl Springer from SwRI. The objective of these meetings was to obtain the assistance, advice, and general support of the manufacturers in the project. As a result of these meetings, agreements were obtained as to engine displacement and selection of the three engines per manufacturer. Through the courtesy of the manufacturers, 1972 model engines were furnished for test. In the case of one manufacturer, the engines were new and in the case of the other, the engines were 125 hour certification engines. Also furnished by the manufacturers were the necessary exhaust piping, muffler, engine mounts, intake air cleaner, etc.

The major area of need for assistance from the manufacturers was in control technology hardware, data, and advice. Here, the manufacturers were unable to furnish more than selected items now used or previously used on light duty car engines. The general lack of help seemed to reflect the low priority given to emission control from gasoline engines in heavy duty service (above 6,000-lb GVW). The manufacturer's inability to furnish any specific or advanced concepts was taken to be a genuine and sincere expression of the current state-of-the-art as of that time. The manufacturers were quite helpful otherwise in assisting SwRI engineers in the course of the laboratory effort in furnishing technical assistance and special

parts when requested. The efforts of the manufacturers must be commended, because without the help given, this project would have been much more difficult to perform. The unqualified thanks of SwRI go to both manufacturers.

C. Project Reviews

A number of meetings, discussions and status reviews were held during the course of this project with the Project Officer. They occurred on March 7th and 30th, June 1st, July 17th and August 16, 1974. These meetings, held on site in the Emissions Research Laboratory, were helpful in overall project management. Monthly progress reports and letter reports were issued to keep the Project Officer fully informed with complete data for analysis. Telephone reports were also made to augment the reports and correspondence.

II. OBJECTIVE AND APPROACH

The objective of this project was to obtain basic emissions data from six currently-produced gasoline-fueled engines and to investigate potentialities for emissions control with two of the more popular engines.

A. Baseline Data

The approach used with the six engines, three each from two manufacturers, was to measure their emission levels or rates using current and experimental test procedures. All engines were 1972 models and were operated on the stationary dynamometer test bed. The test procedure included both operations by the current nine-mode procedure described by the FTP[7] for expression as concentration and in brake specific emissions terms according to the method specified by the California ARB[8, 9]. An experimental 23-mode engine test procedure with expression in grams per bhp-hour (brake specific) was also employed as specified by the Project Officer[10].

B. Control Technology

Two popularly used engines were subjected to a stepwise series of experiments to evaluate the effectiveness of various control approaches singly and in combination. For purpose of evaluation, the primary test procedure was the 23-mode EPA experimental method with nine-mode tests made of the best combination. Methods of control and parameters investigated included basic ignition timing, air-fuel ratio (main jet size variations), exhaust gas recirculation (EGR), oxidation catalysts, and exhaust manifold oxidation by air injection among others.

III. EQUIPMENT, INSTRUMENTS, ENGINES, PREPARATIONS AND PROCEDURES

This section contains a brief description of the instruments, equipment and facilities, engines, preparations and procedures used to conduct this project.

A. Exhaust Sampling and Analysis

Two basic types of exhaust sampling techniques were used during this program. The most familiar set of instruments used was the nondispersive infrared (NDIR) sampling train for raw exhaust gases specified in the Federal Register[7] for the nine-mode cycle (FTP). This system is described first. Another technique used was a variation of the continuous NDIR system in which raw exhaust was also analyzed by flame ionization detector (FID) and chemiluminescence (CL) instruments.

1. Nine-Mode Continuous Sampling, Analysis, and Instrumentation

The exhaust gas sampling and analysis system, for the FTP nine-mode cycle meets the requirements and specifications established in the Federal regulations[7] for heavy-duty vehicle exhaust sampling. A component description of the system is detailed in the above referenced Federal regulations. Nominal full-scale concentration levels for the five NDIR analyzers are as follows:

(1) Low-Range HC - 1000 ppm hexane
(2) High-Range HC - 10,000 ppm hexane
(3) CO - 11 percent
(4) CO_2 - 16 percent
(5) NO - 4000 ppm

Although nitric oxide was not included in the current Federal regulations relating to gasoline HDVs at the time this project was done, this contaminant was important from a research standpoint.

The output of each analyzer is fed to strip-chart recorders. The concentrations from each trace can be obtained from the continuous traces by hand as specified in the nine-mode FTP. The average concentrations are then transferred to computer cards for further processing to obtain composite values for HC, CO, and NO. This method was used as a back-up to the real time computer system normally used. The computer system was designed and assembled by SwRI. This computer utilizes a Data General Super Nova, 8K central processor, and a Computer Products Series RTP 7410 multiplex. The computer program was also prepared by Institute personnel. This computer system was very helpful during this program to determine nine-mode FTP results immediately after completion of the

tests. The reliability and repeatability of the on-line computer has been shown to be equal or better than manual chart reading and computer reduction of data.

The NDIR cart was subjected to a calibration according to EPA requirements. Both static and dynamic gas simulator tests were run initially on this cart by Mr. Matt Maccoche of EPA during the period of September-November, 1971. Frequent calibrations of all NDIR, CL, and FID instruments were made to assure optimum accuracy. One of the EPA checks was to name an unknown contaminant to ± 1 percent, a difficult requirement since the basic detector is only specified to ± 1 percent by the manufacturer. Suffice to say that no tests were made until initial calibrations were satisfactorily completed.

3. Experimental 23-Mode Instrumentation

The use of direct stream, raw exhaust, emission sampling and analysis instruments has ample precedent in the case of NDIR type analyzers in which a fairly dry, clean sample is analyzed. To measure CO and CO_2 by NDIR, the usual continuous NDIR cart used for nine-mode FTP work was used. HC by NDIR was of secondary importance since it is known to grossly understate the HC concentrations in most modes of engine operation. The 23-mode method was to use an FID on the direct tailpipe raw exhaust that has not been cooled below the dew point of the water vapor contained therein. Condensation of water causes severe operational problems and it also is indicative of possible losses of some unburned hydrocarbons by condensation. For gasoline engine exhaust, the industry-accepted practice is to hold the sample, sample lines, and FID analyzers at about 160° F and, of course, no ice-water condensate trap was employed. Good operability at this temperature with an SwRI design HC analyzer had been found on another project dealing with off-road sources for EPA (Contract EHS 70-108).

In a previous project dealing with the 23-mode test[6], it was found that the Beckman Model 400 FID, widely used with diluted gasoline exhaust, was unsuited for raw gasoline engine exhaust. Rather than attempt to modify the instrument with uncertain results, it was decided to use an SwRI design FID and operate same at 160° F. The basic design and theory of operation was discussed in an SAE paper. Please refer to reference 11 for further details and description of the HC instrument.

To improve time response, the SwRI FID oven was located adjacent to the engine exhaust pipe. A fairly short stainless steel sample line, heated by a cylindrical heater, was controlled to maintain a 160° F gas temperature while oven temperature was held at 160° F. The sample probe was of standard design for auto exhaust and located adjacent to the probes used for the CO, CO_2, and NO_x samples.

To monitor the HC sample bypass flow, a small rotameter was connected to the effluent from the FID. Since the water vapor was still in the exhaust and as it tends to condense in the rotameter at room temperature, a small ice trap was added before the rotameter but after the sample was split from the main stream and forced through the sample capillary. This is standard laboratory practice when a flowmeter is used to help monitor sample bypass flow.

A Thermal Electron Corp. (TECO) Model 10A chemiluminescent NO_x-NO analyzer, furnished by EPA, was used to measure NO_x. The TECO instrument analyzed a sample obtained via a separate line from the exhaust pipe. Since water vapor has a sizeable positive interference on the NDIR NO reading, a bone dry sample, commonly achieved by a chemical drying agent such as Aquasorb or Drierite has been standard practice. This has always been a controversial step in sample preparation and the recent trend has been, where possible, to use the chemiluminescent method which does not require it.

The TECO and other commercial chemiluminescent analyzers, however, were not designed to handle raw, undiluted, exhaust and suffer from operational difficulties if the majority of the water vapor is not removed. The current chemiluminescent analyzers operate at room temperature and do well with highly diluted exhaust such as from a constant volume sampler or with atmospheric samples. Raw exhaust contains the water vapor from combustion along with the intake air humidity and removal via an ice-water-type trap is necessary to prevent filling or coating the sample lines and capillary, leading to the reaction chamber, with water.

NO_2 is readily absorbed by water and the efficiency depends on residence and contact area. As the lesser of two evils, an ice-water-type trap with minimal residence time and water-to-sample contact time was used to prevent the sampling lines and other tubing, capillary, etc., within the instrument from becoming water logged. In practice, the same trap used for the NDIR was employed. No chemical drying agent such as Aquasorb or Drierite was used. On several occasions, the effect of the trap on NO_2 was checked by flowing a known concentration of NO_2 span gas through the system at various times during the run with the trap wet and the fiberglass particulate filter "dirty". From this, it was found that on an average about 10 to 15 percent of the NO_2 was lost, making all measurements of NO_2 subject to this error. One solution would be to heat the sample line, pump, etc., from point of sample to entrance of the sample into the reaction chamber.

An analysis of side-by-side NDIR and CL data from a previous project[6] revealed extremely close results and good correlation. The conclusion of such tests was that either system was satisfactory and the CL was preferred since it eliminates the difficult-to-resolve question of the

effect of chemical drying agents on NO readings. The CL is not, however, without certain drawbacks as mentioned earlier.

Figure 1 shows several views of the instruments used for the nine-mode FTP and the 23-mode procedure with stationary-operated engines. The tall cabinet in the upper right and middle right view houses the NDIR NO and the CL NO_x instruments. Shown in the middle right view is the NDIR cart for HC, CO, and CO_2 analysis. The CO and CO_2 analysers in this cart were used both ways, for nine and 23 mode testing. The lower right view shows the oven containing the heated portion of the HC instrument. The pump, filter, valves and detector, etc., are located in the oven with flow control module and electrometer located to the right of the oven.

Shown in the extreme right side of the lower right view is the glassware used to bubble exhaust through reagent for collection of aldehydes. Several runs on each engine, by the 23-mode procedure, included measurement of aliphatic aldehydes by the 3-methyl-2-benzylthiazolone hydrazine (MBTH) method[18, 19]. This is a wet chemical method which is the popularly used technique for aldehyde determination. Its precision and adequacy for raw gasoline exhaust determination has not been thoroughly researched. The method was selected as the best available for a first approximation.

The lower left view in Figure 1 shows the heated sample line used for both HC and aldehyde sample transfer. It was felt important to locate instruments and glassware as close as practical to the exhaust system. All tests were made with samples obtained at a point representing average exhaust system length and the sample lines length kept to a minimum. Usually the sample lines were less than 36 inches. Other views of the instruments will be shown later in the report.

B. Dynamometry and Related Facilities

The two stationary all-electric engine dynamometers used in this project were completely equipped for constant speed motoring-absorbing and could perform the nine-mode FTP and the 23-mode experimental schedules satisfactorily.

1. Baseline Engines

The six baseline engines were operated in Cell 3 of the U. S. Army Fuels and Lubricants Research Laboratory at SwRI. The dynamometer and several typical engine installations are shown in Figures 2 to 4. This Eaton Dynamatic dynamometer is capable of 300 hp absorbing from 2,000 to 5,000 rpm and 50 hp motoring.

2. Control Technology Engines

Both control technology engines were then operated in the Emissions

FIGURE 1. EMISSIONS MEASURING EQUIPMENT USED WITH NINE MODE FTP AND EXPERIMENTAL 23 MODE PROCEDURE

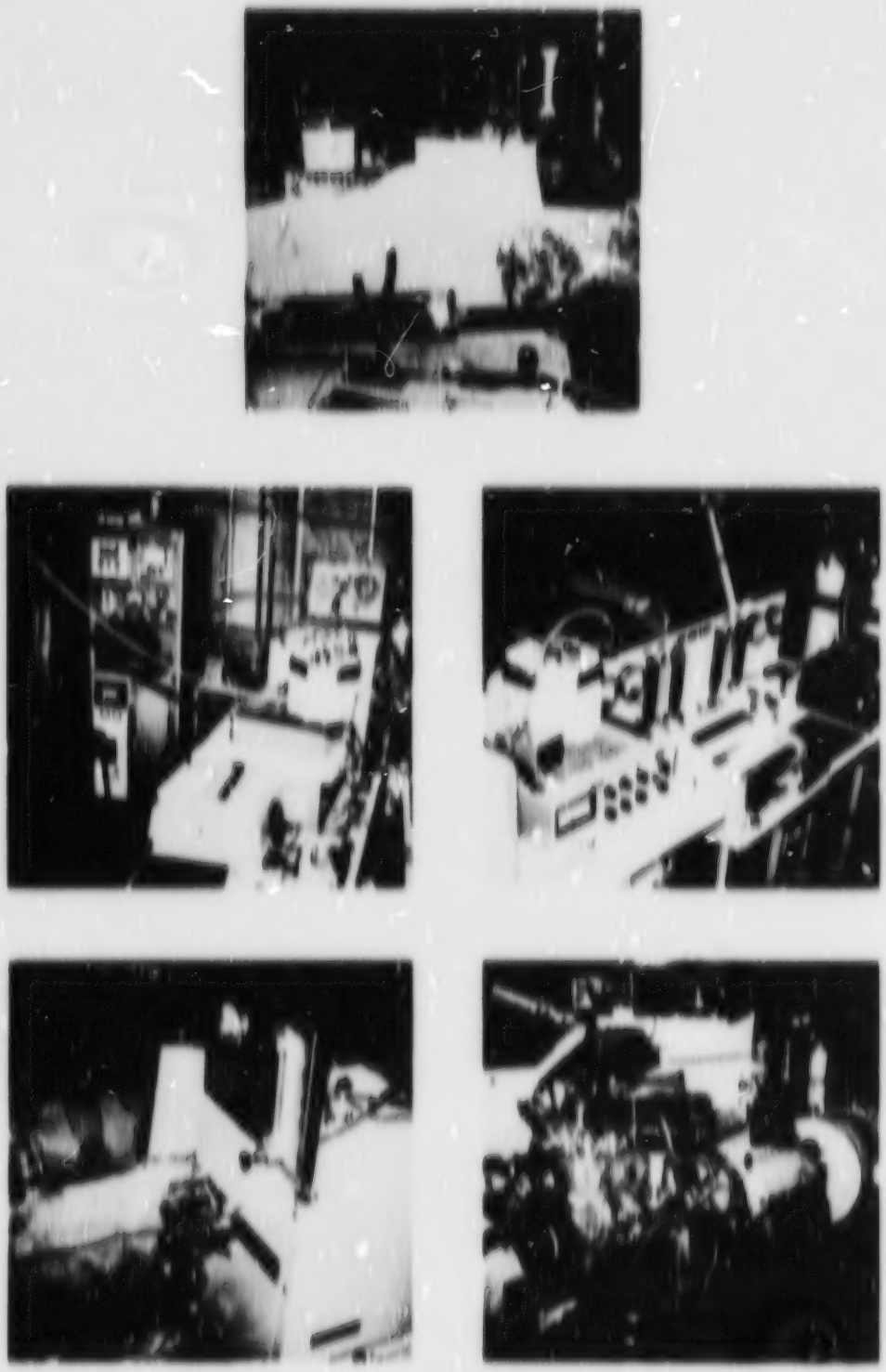


FIGURE 2. BASELINE EMISSIONS TESTS EQUIPMENT AND FACILITIES

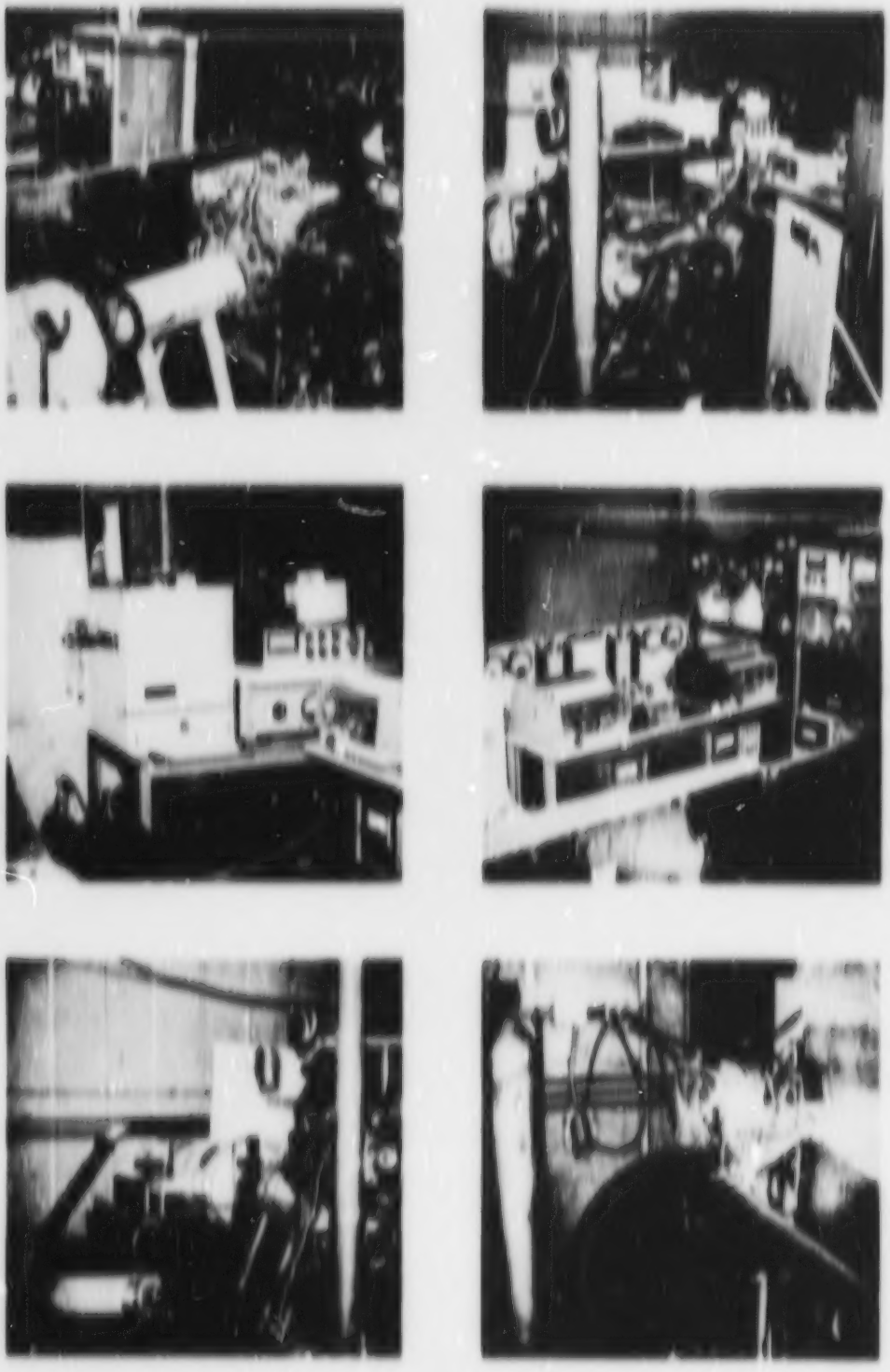


FIGURE 3. DYNAMOMETER AND RELATED INSTRUMENTS AND EQUIPMENT BASELINE TESTS

FIGURE 4. ENGINE UNDER STATIONARY DYNAMOMETER BASELINE EMISSIONS TESTS

Research Laboratory on a similar but larger Eaton Dynamatic dynamometer. This unit has capability to handle 500 hp absorbing (2,000 to 7,000 rpm) with 200 hp motoring. This dynamometer facility will be shown in the various views of engines and control systems later in this report.

3. Related Facilities

As important as the actual emissions measurements are the measurements of engine speed, power output and fuel consumption. The calibrations of the Standard Electric Time Co. speed systems were made by a calibrated strobotac (General Radio) and the hydraulic loading readout system by dead weight test. Fuel flow was measured by a Flo-Tron or weigh scale. Only weigh scale readings for the time (stop watch) to consume a known mass of fuel were used to compute mass emission rates with the baseline engines. A weigh scale calibrated Flo-Tron was used for the control technology engines.

A complete dynamometer installation was provided for measurement and control of engine operating parameters including inlet and outlet water temperature, inlet air temperature, exhaust temperature, oil pressure, exhaust backpressure and intake manifold vacuum. The latter pressure is critical to the nine-mode test and was periodically calibrated against a mercury column. Inlet air humidity was measured using a Bendix Model 566 wet-dry bulb temperature measuring instrument. The Bendix unit was periodically checked against a sling psychrometer. A conventional liquid-in-glass mercury barometer was used to measure barometric pressure and the observed reading suitably corrected.

C. Engines

In all, a total of six engines were obtained through the courtesy of the manufacturers. Two six cylinder in-line engines and four V-8 engines were used in the program. The engines were coded at the request of the manufacturers and with the concurrence of the Project Officer. The characteristics of the engines are listed below.

Test Engine Description

Engine Code	Adv. Flywheel Power[1] Bhp @	rpm	Peak Torque Lb-Ft	rpm	GVW Application Min - Max, lbs
1-1	132	3500	239	2000	6,200 - 24,000
1-2	217	3200	398	1800	23,000 - 80,000[2]
1-3	152	3600	278	2200	16,000 - 50,000[2]
2-1	110	3800	185	1600	6,200 - 16,000
2-2	230	4000	360	2400	21,000 - 64,000[2]
2-3	175	4000	290	2400	6,200 - 26,000

[1] SAE J-245 (net)
[2] Gross Combined Weight

Engines 1-1 and 2-1 were used in the control technology assessment portion of the project. All engines were truck or truck version 1972 model year engines and had been built under the provisions of the 1972 certification regulations. Engines 1-1, 1-2, and 1-3 were the 125 hour certification engines. All engines were furnished to SwRI by the manufacturers along with necessary engine mounts, clutch-flywheel where desired and exhaust piping.

D. Preparations

The six engines subjected to baseline emissions measurements were provided by the manufacturers in ready-to-run condition. Since engines 2-1, 2-2, and 2-3 were new, a 10 hour break-in was given these engines before starting the emission test series. The variable speed and load run-in schedule was in accord with the manufacturer's recommendations. Once the engine was run-in or checked to make certain it was operating properly, the basic timing and idle speed were checked to make certain their adjustments were within the EPA factory sticker tune specifications. If not, adjustments were made. No adjustments were made to the idle air screws. These engines and carburetors were furnished with the usual plastic idle air screw adjustment limiters.

E. Fuels

The leaded premium fuel used during all baseline and control technology emissions tests met the requirements of the Federal Register[6]. A typical fuel analysis of the fuel used and purchased locally is given in Table 1. Also shown on Table 1 is an inspection of the low lead Indolene clear motor fuel used in all control technology experiments involving the oxidation catalyst.

F. Experimental Procedures

All the engines were subjected to two basic laboratory stationary-operated engine procedures.

1. Nine-Mode FTP Schedule

The 1970 FTP (nine-mode 2,000 rpm constant speed procedure) is adequately described in the Federal Register[7]. The test schedule is listed in Table 2. The procedure is 20 minutes in length and consists of the Table 2 schedule being run four times. The weighting factors, listed in the last column, are used to calculate the concentration results.

Please note that in reality, only six modes, of which only three are power-producing, are included in this 2,000 rpm constant speed procedure. The 16-inch condition is repeated four times for 15.6 percent of the weight. The other power-producing modes, Modes 3 and 7, the 10-inch and 3-inch

TABLE 1. FUEL INSPECTION RESULTS

	Leaded	Clear
Gravity, deg API (D287)	59.3	58.0
Distillation Range (D86)		
Initial Boiling Point, ° F	88	86
5% Point, ° F	116	
10% Point, ° F	127	128
20% Point, ° F	150	
30% Point, ° F	175	
40% Point, ° F	200	
50% Point, ° F	220	220
60% Point, ° F	235	
70% Point, ° F	254	
80% Point, ° F	276	
90% Point, ° F	305	315
95% Point, ° F	327	
End Point	340	409
% Recovery	98.0	98.0
% Residue	1.0	1.0
% Loss	1.0	1.0
Octane No., Research (D1656)	103.4	98.3
Total, % wt (D1266)	0.004	0.01
Reid Vapor Pressure, psi (D323)	9.1	9.2
Hydrocarbon Composition (D1319)		
Olefins, %	0.4	3.0
Aromatics, %	27.3	30.0
Saturates, %	72.3	7.0
Lead (Organic) g/gal (D526)	3.271	0.01
Phosphorus, Theory	0.0	0.0
Oxidation Stability (D525)	600+	
Existent Gum, mg (D381)	0.6	0.2

TABLE 2. CURRENT FEDERAL NINE-MODE CONSTANT SPEED PROCEDURE FOR HEAVY DUTY GASOLINE TRUCKS

Sequence Number	Manifold Vacuum	Time in Mode, sec	Cumulative Time, sec	Weighting Factors
1	Idle	70	70 (1:10)	0.036
2	16 in. Hg	23	93 (1:33)	0.089
3	10 in. Hg	44	137 (2:17)	0.257
4	16 in. Hg	23	160 (2:40)	0.089
5	19 in. Hg	17	177 (2:57)	0.047
6	16 in. Hg	23	200 (3:20)	0.089
7	3 in. Hg	34	234 (3:54)	0.283
8	16 in. Hg	23	257 (4:17)	0.089
9	Closed Throttle	43	300 (5:00)	0.021

Engine Speed 2000 ± 100 rpm.

An initial 5-min idle, two warmup cycles and two hot cycles constitute a complete dynamometer run.

modes, account for another 54 percent of the schedule. The three power modes, 16-inch, 3-inch, and 10-inch vacuum, represent a total of 89.6 percent of the cycle weight. The idle (3.6 percent weight), 19 inch (4.7 percent weight) and the closed throttle (2.1 percent weight) represent the remaining 10.4 percent of the cycle weight.

4. Experimental 23-Mode Schedule

The experimental 23-mode schedule is listed on Table 3 and is taken directly from the preliminary procedure, reference 10, provided by the Project Officer. A copy of this reference is included as Appendix Y. Note that modes 7, 9, and 10, at 1200 rpm engine speed, and modes 18, 20, and 21, at 2300 rpm engine speed, carry a zero weighting factor. Modes 7, 9, 10, 18, 20 and 21 were measured to obtain emission data that may be of use later. The 23-mode schedule and procedure is quite similar to the 1500-2500 rpm schedule studied earlier in the basic project and described in detail in the final report[6].

Although a 230 minute long, ten minutes per mode, test was described by the preliminary procedure, earlier work indicated that three minute long modes were quite adequate for an engine mapping-type procedure. As described in the final report[6] dealing with procedural development, the first minute is devoted to changing speed and load, the second minute for stabilization and only the time average of the third minute emission concentration used.

When measuring aliphatic aldehydes, a three-minute sampling period is needed and the three-minute schedule is extended to six minutes, with the third, fourth, and fifth minutes given over to wet collection of aldehydes. The sixth minute and first and second minutes of the next mode were used to wash down the fritted bubblers and exchange the bubbling reagent and holders.

Note that 15 minutes are allocated to mode 15. The additional nine minutes are provided to allow the HC analyzer and sampling system to purge after the very high HC concentration closed throttle (CT) raw exhaust samples have been analyzed. This procedure was found to be quite acceptable with regard to HC hang-up and is felt a necessary part of measuring the very high CT conditions.

One item that would have been helpful and is felt necessary for future 23-mode procedure work is a dual range CO or two different CO instruments. A 0-11 percent CO instrument is necessary under the WOT conditions, while at optimum combustion efficiency, such as about 50 to 75 percent power, a much lower, say 0-1 percent CO instrument could be employed for improved accuracy. The situation is somewhat similar to the nine-mode NDIR HC instruments where two are needed, one for CT and selected other modes on

TABLE 3. EXPERIMENTAL 23 MODE EMISSIONS TEST SCHEDULE
(Heavy Duty Gasoline Engines)

Mode	Engine Speed, rpm	Power Out, %*	Mode Time	Cumulative Time	Weighting Factor
1	Idle	0	3	3	0.07
2	1200	2	3	6	0.06
3	1200	8	3	9	0.06
4	1200	18	3	12	0.05
5	1200	25	3	15	0.03
6	1200	50	3	18	0.06
7	1200	75	3	21	0.06
8	1200	82	3	24	0.04
9	1200	92	3	27	0.00
10	1200	100	3	30	0.00
11	Idle	0	3	33	0.07
12	1200	0 (CT)**	12	45	0.12
13	2300	100	3	48	0.025
14	2300	92	3	51	0.035
15	2300	82	3	54	0.035
16	2300	75	3	57	0.06
17	2300	50	3	60	0.06
18	2300	25	3	63	0.00
19	2300	18	3	66	0.065
20	2300	8	3	69	0.00
21	2300	2	3	72	0.00
22	Idle	0	3	75	0.08
23	2300	0 (CT)**	3	78	0.06

*Observed at the flywheel, percent of maximum at a given engine rpm.
**Power out is zero. Engine requires motoring in this mode.

occasion,while all others are read on a 0-1000 ppm scale. A multirange unit like a 315 B Beckman is only good to a five times factor, making easy 0-1 and 0-11 percent impossible by merely the range gain amplification. Either stacked cells or two separate instruments is the answer in this regard.

3. Engine Test Method

The specific test procedure followed for a baseline engine, assuming the engine has been proof tested with power, torque, fuel rate, etc., as expected and any run-in or break-in completed, was essentially as follows:

First, replicate nine-mode tests were made, at least three times with one hour shut down between tests. The full 20 minute schedule was followed. Then, the engine power settings and fuel consumption rates were determined in replicate. These measurements are necessary to convert the nine-mode concentrations to grams per bhp-hour using the carbon balance method specified in the California ARB Procedure[18, 9]. It is not possible to measure the fuel accurately during the fairly busy nine-mode schedule (see Table 2 for mode times) and therefore, such measurements are normally obtained at the conclusion of the test.

Next, NO NDIR and both NDIR HC analyzers were switched out and the NO-NO_2 CL and heated FID were switched into the sampling and analysis system. The 23-mode procedure calls for operation at specific percentages of maximum power at 2300 and 1200 rpm. As soon as the engine was thoroughly warmed up, the maximum observed flywheel power output of the engine was determined by operating alternatively at WOT at 1200 rpm and 2300 rpm.

In actual operation, the 23-minute procedure was preceded by a 10-minute operation at 2000 rpm, half-load to warm up the engine. During the last few minutes, the analyzers were zeroed and spanned, ice-water traps drained and filters renewed. The engine then began the initial idle mode of the 23-mode test. In practice, the test was not difficult since the first minute of each 3-minute mode was allocated to adjust engine speed and load, the second minute was devoted to engine-emission stabilization, and the final minute the emissions were continuously recorded and integrated to determine modal concentrations.

More than 3 minutes may be used at the center idle, mode 11, to do maintenance on the sampling and analysis equipment. Normally, as soon as the first closed throttle was complete, Mode 12, the HC system was purged with zero N_2 while other instruments were spanned and zeroed. Then the HC instrument was spanned and zeroed, water traps were drained, filters replaced, and all instruments rechecked for zero and span before starting Mode 13. At any mode during the test, the instruments could be zeroed and spanned, if desired, as long as it was done during the first 1-1/2

minutes of the mode. In practice, the ice-water traps were drained after the 5th and 17th modes of the test.

G. Calculational Procedures

The emission results were calculated in three ways:

1. Nine-Mode FTP - Concentrations

The calculations of the final result of ppm n hexane HC, and percent CO followed the nine-mode procedure as specified in detail by the Federal Register[7]. In effect, the raw NDIR readings in ppm are adjusted by a dilution factor

$$\text{Dilution Factor} = \frac{14.5}{CO_2\,\% + 0.5\,(CO\,\% + 10.8\,HC\,\%\ \text{n hexane})}$$

and then multiplied by the appropriate weighting factor. These were listed earlier in Table 2.

The on-line process computer was normally used with manual strip chart-computer reduction as an alternative. The computer print-out is so arranged to list as-measured raw concentrations, the adjusted, weighted and sum composite values. Since this is a standard method, the reader is referred to Reference 7 for complete details. Table 4 is an explanation of the nine-mode FTP concentration computer print-outs.

Although not covered by current Federal regulations, NO during the nine-mode FTP was measured by NDIR. The results were treated the same as the CO and HC, i.e., adjusted for dilution and application of the weighting factor. Since water vapor or inlet air humidity has a measurable effect on NO formation in combustion engines, this reading is normally presented both on an observed and corrected basis. The conventional correction basis is 75 grains of water per pound of dry air absolute humidity and is determined by multiplying the observed NO by the correction factor

$$\text{Correction Factor (K)} = 0.6272 + 0.00629H - 0.000017\,6H^2$$

where H = absolute humidity of the air

This expression is identical to that in the current heavy-duty gasoline truck surveillance project (Contract EHS 70-113). The factor came from results of an AMA project described in Reference 14.

2. Nine-Mode ARB - Brake Specific

This method, described in References 8 and 9 utilizes the carbon

TABLE 4. EXPLANATION OF NINE-MODE FTP CONCENTRATION COMPUTER PRINTOUT SHEETS

1. Column Explanation

Column	Column Title	Explanation
1	FEDERAL MODE	Mode number and inlet vacuum (inches of mercury)
2	AS MEASURED HC	Measured hydrocarbon emissions, ppm or n-hexane
3	AS MEASURED CO	Measured carbon monoxide emissions in percent
4	AS MEASURED CO_2	Measured carbon dioxide emissions in percent
5	AS MEASURED NO	Measured nitrogen oxide emissions in ppm
6	DILUTION FACTOR	Dilution factor for each mode calculated by equation shown at bottom of printout
7	ADJUSTED HC	Measured HC times the dilution factor (PPM-hexane)
8	ADJUSTED CO	Measured CO times the dilution factor (percent)
9	ADJUSTED NO	Measured NO times the dilution factor (PPM)
10	WEIGHTING FACTOR	Weighting factor assigned to each mode
11	WEIGHTED HC	Adjusted HC times weighting factor
12	WEIGHTED CO	Adjusted CO times weighting factor
13	WEIGHTED NO	Adjusted NO times weighting factor

2. Line Explanation

1st Line

(X) - (XX) - 72	Date in month, day and year
ENGINE (X) - (X)	SwRI engine identification number
RUN (X)	Run Number. Runs numbered sequentially. The first run for a given day is run 1.

TABLE 4 (CON'T). EXPLANATION OF NINE-MODE FTP CONCENTRATION COMPUTER PRINTOUT SHEETS

K = (X.XX)	Humidity correction factor for cycle composite NO_x. K = .6272 + .00629 H − .000176H^2. Where H = absolute humidity in grams/lb DA
HUM = (XXX) GR/LB	Absolute humidity in grams/lb DA during run
Line Starting SUM - CYCLE COMPOSITE	Sumation of each weighted emission type
AVERAGE SUM = (COMPOSITE VALUES FOR CYCLES 1 AND 2)	$\frac{\text{SUM (cycle 1)} + \text{SUM (cycle 2)}}{2}$
AVERAGE SUM = (COMPOSITE VALUES FOR CYCLES 3 AND 4)	$\frac{\text{SUM (cycle 3)} + \text{SUM (cycle 4)}}{2}$
FOUR CYCLE COMPOSITE	Composite value for each emission using formula shown
CORRECTED NO	Composite NO times K

balance method to establish the exhaust mass rate. It is necessary to know precisely the fuel consumption rate as well as CO, CO_2, and HC, the principal carbon-bearing products of combustion. Since it is desired to express the emission rate on a brake specific basis in terms of grams of contaminant per brake horsepower-hour, it is also necessary to accurately measure or know the power output at the flywheel. With the modal concentrations (raw) from the nine-mode test and the fuel rate and power output modally, the determination of mass rates by the 1974 FTP is a straightforward calculation. A computer was used and the print-out sheets are explained on Table 5.

All data presented in this report use the latest density, correction factor for NO_2 and weighting factors per Reference 9. The correction factor

$$K = 0.634 + 0.00654H - 0.0000222H^2$$

where H is the grains of water per pound of dry air was used to correct observed NO to NO at 75 grains humidity, standard.

Reference 9 also changed the weighting factors from those historically used with the California and Federal nine-mode test for weighting the emission concentrations. Because of the importance of weighting factors on the final result, the current ARB weighting factors are listed along with the FTP weighting factors.

ARB Weighting Factors for Nine-Mode Mass Emissions

Mode	Vac. in Hg	Previous*	Current
1	Idle	0.036	0.232
2	16	0.089	0.077
3	10	0.257	0.147
4	16	0.089	0.077
5	19	0.047	0.057
6	16	0.089	0.077
7	3	0.283	0.113
8	16	0.089	0.077
9	C.T.	0.021	0.143

*Currently used in the FTP[7] and contained in earlier ARB proposals[8].

In essence, the latest California ARB factors give substantially more weight to closed throttle and idle modes and less weight to the 10-inch and 3-inch modes. Recall that neither the idle or closed throttle are power producing, with the net effect that cycle power is less when weighted making the denominator smaller and the quotient larger.

TABLE 5. EXPLANATION OF NINE-MODE FTP
BRAKE SPECIFIC COMPUTER PRINTOUT SHEETS

1. Column Explanation

Column:	Column Title	Explanation
1	MASS MODE	Mode number and inlet vacuum (inches of mercury)
2	AS MEASURED HC	Measured hydrocarbon emissions, ppm or n-hexane
3	AS MEASURED CO	Measured carbon monoxide emissions in percent
4	AS MEASURED CO_2	Measured carbon dioxide emissions in percent
5	AS MEASURED NO	Measured nitrogen oxide emissions in ppm
6	TOTAL CARBON	The percentage of exhaust gas that is carbon containing gases
7	FUEL CONS.	Engine fuel consumption in Grams/Hr.
8	ADJUSTED (MASS) HC	Hydrocarbon emissions in Grams/Hr. calculated from measured HC
9	ADJUSTED (MASS) CO	Carbon monoxide emissions in Grams/Hr. calculated from measured CO
10	ADJUSTED (MASS) NO_2	Nitrogen dioxide emissions in Grams/Hr. calculated from measured NO
11	WT. FACT.	Weighting factor for each mode
12	WEIGHTED (MASS) HC	Hydrocarbon emissions in Grams/Hr. times the weighting factor
13	WEIGHTED (MASS) CO	Carbon monoxide emissions in Grams/Hr. times the weighting factor
14	WEIGHTED (MASS) NO_2	Oxides of nitrogen emissions as NO_2 Grams/Hr. times the weighting factor
15	HP	Engine horsepower from dynamometer

TABLE 5 (CONT.) EXPLANATION OF NINE-MODE FTP BRAKE SPECIFIC COMPUTER PRINTOUT SHEETS

Line Explanation	Explanation
1st Line	
(X) - (XX)-72	Date in month, day and year
ENGINE (X)-(X)	SwRI engine identification number
RUN (X)	Run number. Runs numbered sequentially. The first run for a given day is run 1.
K = (X.XX)	Humidity correction factor for cycle composite NO_x. $K = .634 + .00654\,H - .0000222H^2$. Where H = absolute humidity in grams/lb DA
HUM = (XXX) GR/LB	Absolute humidity in grams/lb DA during run
Line Starting	
SUM - CYCLE COMPOSITE	Grams/BHP-HR for cycle, sumation of each weighted emission divided by the sumation of horsepower times weighting factor, i.e. $\frac{\sum \text{Emission} \times W.F.}{\sum H.P. \times W.F.}$
AVERAGE SUM -(COMPOSITE VALUES FOR CYCLES 1 AND 2)	$\frac{\text{SUM (cycle 1)} + \text{SUM (cycle 2)}}{2}$ Grams/BHP-HR
AVERAGE SUM -(COMPOSITE VALUES FOR CYCLES 3 AND 4)	$\frac{\text{SUM (cycle 3)} + \text{SUM (cycle 4)}}{2}$
FOUR CYCLE COMPOSITE	Composite of all four cycles in Grams/BHP-HR using formula shown
CORRECTED NO_x	Four cycle composite NO_x in grams/BHP-HR times the humidity correction factor, K.

3. Experimental 23-Mode Calculations

This experimental procedure and its calculational method was provided by the Project Officer for use in this project[10]. The calculational methods followed fairly closely those established for the 23-mode procedure used in Reference 6. The engine speeds were slightly lower, the power levels changed and the weighting factors were different but the method of calculation, using the carbon balance technique, remained the same. As a consequence of correspondence between Mr. Mel Ingalls of Southwest Research Institute and Mr. John Rosek of Environmental Protection Agency, the calculation procedure for the 23-mode data was clarified. As confirmed by letter from Mr. Ingalls to Mr. Rosek on April 17, 1972, all data was expressed on a dry basis.

Table 6 is an explanation of the computer print-out sheets and illustrates how the final grams of HC, CO, or NO_2 were determined from the raw concentrations, fuel rate and power output data. Note that the print-out includes aldehydes so that this emission could be expressed on a brake specific basis of grams of formaldehyde per bhp-hour. The colorimetric determination of aliphatic aldehydes is in terms of the simplest aldehyde, formaldehyde.

Beginning with engine 2-3, the last baseline and the first control technology engine, the computer print-out included air-fuel ratio (AFR) by the Spindt calculation method. This is listed on the computer print-out where fuel in grams per hour once was. This addition to the print-out information necessitated the addition of O_2 measurement by a Beckman polarographic method. The Spindt Calculation is included in the explanation of the 23-mode computer print-out, Table 6. For additional description of this method, please refer to Reference 15. The air-fuel ratio computed by this method agrees with the air-fuel ratio calculated by one other method and was felt reliable enough for purposes of this project. All of the calculational methods used in this project were discussed in detail with the Project Officer and his approval obtained for their use. Changes in print-out format, factors, corrections, etc., were effected when requested to conform with the latest procedures and methods available to EPA and SwRI.

TABLE 6. EXPLANATION OF EXPERIMENTAL 13 MODE BRAKE SPECIFIC COMPUTER PRINTOUT SHEETS

Column	Column Label	Explanation
Upper table		
1	MODE	Mode number (1-13)
2	SPEED	Engine speed in rpm
	DYNAMOMETER LOAD	Measured dynamometer load in ft-lbs
4	HP	Horsepower calculated from dynamometer load and speed using equation: $HP = \frac{(ft\text{-}lbs) \times rpm}{5252}$
5	MAN. VAC.	Measured manifold vacuum in inches of Mercury
6	FUEL RATE LB/HR	Measured lb/hr of fuel used
7 *	FUEL RATE GM/HR	Fuel rate in grams per hour calculated from equation: GM/HR = 453.6 x lbs/hr
8	DRY CONCENTRATION ALDE	Measured aldehyde emission concentration as formaldehyde (ppm) corrected to a dry (water from combustion removed) basis by the equation: ALDE = ALDE (as measured wet) x K_1 where $K_1 = \frac{(100 + .9\,25\,(CO\% + CO_2\%)}{100}$
9	DRY CONCENTRATION HC	Measured hydrocarbon emission concentration (ppmC) corrected to a dry basis as above.
10	DRY CONCENTRATION CO	Measured carbon monoxide emission concentration, % by volume. Measured dry with water of combustion removed.
11	DRY CONCENTRATION CO_2	Measured carbon dioxide emission concentration, % by volume. Measured dry.
12	DRY CONCENTRATION NO_x	Measured oxides of nitrogen emission concentration as NO (ppm). Measured dry.

TABLE 6. (Cont'd) EXPLANATION OF EXPERIMENTAL 23 MODE BRAKE SPECIFIC COMPUTER PRINTOUT SHEETS

Column	Column Label	Explanation
Lower Table		
1	MODE	Mode number (1-23)
2	CALCULATED GRAM/HR ALDE	Calculated aldehyde emission concentration as formaldehyde in grams/hr $ALDE(gm/hr) = .16 \times \frac{ALDE}{10000} \times \frac{\text{fuel flow(grams/hr)}}{\text{total carbon}}$ where Total Carbon = $CO_2\% + CO\% + \frac{HC(ppm)}{10000}$
3	CALCULATED GRAM/HR HC	Calculated hydrocarbon emission concentration in grams/hr $HC(gm/hr) = \frac{HC}{10000} \times \frac{\text{fuel flow(grams/hr)}}{\text{total carbon}}$
4	CALCULATED GRAM/HR CO	Calculated carbon monoxide emission concentration in grams/hr $CO = .028 \times CO \times \frac{\text{fuel flow(grams/hr)}}{\text{total carbon}}$
5	CALCULATED GRAM/HR NO_2	Calculated oxides of nitrogen emission concentration as NO_2 in grams/hr $NO_2 = 3.38 \times \frac{NO}{1000} \times \frac{\text{fuel flow(grams/hr)}}{\text{total carbon}}$
6	WT. FAC.	Weighing factor for each mode
7	WT. HP	Weighted horsepower. HP (Column 4) times weighting factor (Column 16)
8	BRAKE SPECIFIC ALDE	Aldehyde, gm/hr, (Column 2) divided by HP (Column 4, upper table) for the individual mode. "R" in table indicates indeterminate value.
9	BRAKE SPECIFIC HC	HC, gm/hr, (Column 3) divided by HP (Column 4, upper table) for the individual mode
10	BRAKE SPECIFIC CO	CO, gm/hr, (Column 4) divided by HP (Column 4, upper table) for the individual mode.
11	BRAKE SPECIFIC NO_2	NO_2, gm/hr, (Column 5) divided by HP (Column 4, upper table) for the individual mode.

TABLE 5. (Cont'd) EXPLANATION OF EXPERIMENTAL 23 MODE BRAKE SPECIFIC COMPUTER PRINTOUT SHEETS

CYCLE COMPOSITE	Explanation
HC, CO, NO_2, ALDE	Summation of emission for each mode times weighting factor divided by summation of weighted horsepower for each mode. $$\frac{\sum_{i=1}^{23} \text{Emission}_{(i)} \times W.F._{(i)}}{\sum_{i=1}^{23} HP_{(i)} \times W.F._{(i)}}$$
BSFC	Summation of fuel flow (lbs/hr) times weighting factor for each mode divided by summation of weighed horsepower for each mode. $$\frac{\sum_{i=1}^{23} \text{Fuel flow (lb/hr)}_{(i)} \times W.F._{(i)}}{\sum_{i=1}^{23} HP_{(i)} \times W.F._{(i)}}$$

* For engine 2-3, this column was replaced with air-fuel ratio by the Spindt calculation formula and all control technology data includes AFR by this method.

$$FR(i) = \frac{(CO(i) + CO_2(i))}{TC(i)}$$

$$AFR = FR\left\{9.0831\left[\frac{\left(1 + \frac{CO(i)}{3(CO_2(i))} + \frac{O_2(i)}{CO_2(i)}\right)}{1 + \frac{CO(i)}{CO_2(i)}}\right] + \left[\frac{15.8}{3.5 + \frac{CO(i)}{CO_2(i)}}\right]\right\}$$

IV. RESULTS

The results of this project are presented in two segments; the first, covering the six baseline engines and the second, the control technology experiments with two engines.

A. Baseline Results

The baseline results for all six engines are described by the type of test conducted namely, FTP concentration, FTP mass and 23-mode mass.

1. Nine-Mode FTP Concentration

Table 7 is a complete listing of the nine-mode results in terms of ppm n hexane, percent CO and ppm NO observed and corrected. The replicate run data for each engine is listed by engine in the order tests were run. An average of the three run results is shown and may be directly compared to the current 1972 limits of 275 ppm n hexane and 1.5 percent CO. For a given engine, the test repeatability was judged normal and satisfactory.

Different engines had different emissions behavior with the range in HC from 88 to 234 ppm n hexane, the range in CO from 0.31 to 1.42 percent, and the range in corrected NO from 1323 to 2174 ppm. Engine 1-1, 1-2, and 1-3 results compare favorably with certification results. Little more can be said about these results, except to compare them to proposed standards of 160 ppm n hexane, 0.8 percent CO and 2,000 ppm NO (corrected) published in the October 5, 1971 Federal Register.(16)

2. Nine-Mode FTP Mass Emissions

Table 8 summarizes the replicate runs made on the six baseline engines in the order tested. It is difficult to make many comments on the results relative to the 1973 California and 1974 Federal limits of 40 grams of CO per bhp-hour and 16 grams of HC + NO_2 (corrected). The range of CO was 14.8 to 69.2 grams per bhp-hour and the range of HC + NO_2 was 14.6 to 21.3 grams per bhp-hour. Most engines appear to have little problem in meeting the CO and are nearly there on HC + NO_2. Generally, the manufacturers try to have a fairly good margin between the engine emissions rate and the limits.

What action will be taken by the manufacturers to meet 1975 California limits of 25 grams CO and 5 grams HC + NO_2 per bhp-hour is unknown at this time. It would seem that substantial improvements will be necessary to meet the apparently stringent 5 gram standard. Just as the nine-mode FTP concentration run-to-run repeatability was good, so was the repeatability good for the mass calculations. The fuel rate and power levels are nearly constant so that only raw emission concentrations have an effect on run-to-run repeatability. The FTP mass rates "track" the concentrations as would be expected.

TABLE 7. NINE-MODE FTP EMISSION RESULTS
CONCENTRATIONS PER FTP

Engine	Date	Run	HC ppm Hex	CO %	Observed NO_x ppm	Corrected NO_x ppm	Humidity gr/lb d. a.
A-1	3/6/73	1	90	0.35	2188	2041	58
A-1	3/6/73	2	95	0.29	2052	1998	68
A-1	3/6/73	3	80	0.29	2071	2032	70
		Average	88	0.31	2104	2024	
1-1	3/21/73	1	112	0.39	2020	1908	60
1-1	3/21/73	2	99	0.40	2132	1980	57
1-1	3/21/73	3	106	0.58	2691	2641	70
		Average	106	0.44	2281	2174	
1-2	4/6/73	2	228	0.71	1894	2052	101
1-2	4/6/73	3	233	0.71	1934	2153	113
1-2	4/6/73	4	240	0.70	1988	2163	103
		Average	234	0.71	1939	2123	
2-2	4/14/73	2	163	1.42	1173	1313	116
2-2	4/14/73	3	164	1.43	1227	1364	112
2-2	4/14/73	4	170	1.44	1177	1290	106
		Average	169	1.42	1198	1324	
1-3	4/24/73	1	117	0.36	1825	1517	36
1-3	4/25/73	2	124	0.30	1749	1578	51
1-3	4/25/73	3	114	0.27	1836	1488	32
		Average	119	0.31	1803	1528	
2-3	5/12/73	1	111	0.66	1411	1593	120
2-3	5/12/73	2	110	0.65	1398	1589	124
2-3	5/12/73	3	126	0.67	1438	1632	122
		Average	116	0.66	1414	1601	
	1972 Limit (Fed)		275	1.5	No Standard		

TABLE 8. NINE-MODE EMISSION RESULTS
PER 1974 FTP CALCULATION PROCEDURE

Engine	Date	Run	Grams/bhp-hr HC	CO	Obs. NO_x	Corr. NO_x	Corr. HC+NO_x	Humidity gr/lb d.a.
4-1	3/6/72	1	3.28	17.3	15.6	14.6	17.9	58
4-1	3/6/72	2	3.41	13.5	14.7	14.3	17.7	68
4-1	3/6/72	3	2.76	13.5	14.8	14.5	17.3	70
		Average	3.15	14.8	15.0	14.5	17.6	
1-1	3/21/72	1	3.24	17.0	13.4	12.6	15.9	60
1-1	3/21/72	2	2.88	16.6	14.1	13.2	16.0	57
1-1	3/21/72	3	3.10	21.2	17.8	17.5	20.6	70
		Average	3.07	18.3	15.1	14.4	17.5	
1-2	4/6/72	2	7.16	32.8	12.7	13.6	20.7	101
1-2	4/6/72	3	7.30	32.7	13.1	14.1	21.5	113
1-2	4/6/72	4	7.46	32.2	13.3	14.3	21.8	103
		Average	7.33	32.6	13.0	14.0	21.3	
4-2	4/14/72	2	5.62	69.3	9.1	10.0	15.6	116
4-2	4/14/72	3	5.61	69.4	9.6	10.4	16.0	112
4-2	4/14/72	4	5.88	68.9	9.2	9.9	15.8	106
		Average	5.70	69.2	9.3	10.1	15.8	
1-3	4/24/72	1	4.42	18.3	14.4	12.1	16.5	36
1-3	4/25/72	2	4.71	15.3	13.8	12.6	17.3	51
1-3	4/25/72	3	3.45	13.9	14.5	11.9	16.4	32
		Average	4.53	15.8	14.3	12.2	16.7	
4-3	5/12/72	1	3.22	31.2	10.2	11.2	14.4	120
4-3	5/12/72	2	3.23	31.1	10.1	11.1	14.3	124
4-3	5/12/72	3	3.63	31.9	10.3	11.5	15.0	122
		Average	3.36	31.4	10.2	11.2	14.6	
1973 Limit (Cal.)				40			16	
1975 Limit (Cal.)				45			5	

The analysis made using the FTP procedure indicated that it is very sensitive to fuel rate, especially HC results. Low fuel rates occur at idle, CT, and 19 inch vacuum modes where HC are generally high. A small error in fuel rate can make a severe error in the HC results. Since only three modes actually produce measurable power, the 16, 10, and 3 inch modes, the cycle composite is quite dependent on precise power measurements.

3. Experimental 23-Mode Mass Emissions

Table 9 contains summary data for the many replicate runs made to determine baseline emissions from the six engines by the experimental 23-mode procedure. The overall run-to-run repeatability seemed satisfactory for HC, CO, and NO_2. A comparison against a target or desired level is not possible since, at this writing, none exist.

Measurement of aldehydes was attempted and though the overall run-to-run results look good, the modal concentration repeatability was not very good. The problem of trying to measure aldehydes by MBTH was of continual concern during this project. Calibration of the entire system using bags of air + trace quantities of formaldehyde have given routine precision of ± 10 to 15 percent normally. Some if not most of the lack of repeatability must be due to the engine and the remainder to the sampling, gas washing and colorimetric analysis. It is uncertain whether the MBTH approach is satisfactory, but it is the best known method for measurement of repetitive samples.

The following is an engine-by-engine summary of the general operation and experience regarding the 23-mode test.

(a) Engine 2-1: Testing of this engine began on March 6, 1972 with the running of the nine-mode Federal test. Prior to making the tests, a 25 hour break-in at various speeds and loads (according to a schedule used by the manufacturer) was completed. The basic timing and engine idle speed was then adjusted to that specified by the manufacturer, namely 4° BTDC and 700 rpm. Three runs were then made with satisfactory run-to-run and mode-to-mode agreement. Generally speaking plus or minus ten percent of the mean is acceptable with plus or minus five percent of the mean excellent test repeatability. There is no hard and fast rule since test repeatability is dependent on engine, procedure and exhaust contaminant.

Eight runs were made using the 23-mode procedure of which seven were used. The large number of runs were possible because of the delay in receiving additional engines for test. This allowed certain instruments to be checked for repeatability. HC, CO, NO_2, and aldehydes exhibited mode-to-mode variability (one run had to be discarded), but on an overall test brake specific basis, the run-to-run repeatability looked good. Little more can be

TABLE 9. EXPERIMENTAL 23-MODE PROCEDURE DRY CORRECTED EMISSION RESULTS

Engine	Date	Run	Grams/Bhp-Hr HC	CO	NO_x Obs.	Alde.	Cycle Weighted BSFC	Humidity gr/lbd.a.
2-1	3/8/72	2	12.17	53.0	12.0	-	0.750	61
2-1	3/8/72	3	11.02	49.2	12.4	-	0.750	55
2-1	3/9/72	1	9.50	40.7	13.4	0.130	0.750	44
2-1	3/9/72	2	9.16	46.4	13.4	-	0.148	59
2-1	3/10/72	1	9.11	46.4	11.2	0.128	0.750	73
2-1	3/13/72	1	9.50	47.7	10.2	-	0.750	94
2-1	3/13/72	2	9.88	51.3	10.9	-	0.750	101
	Average		10.05	47.8	11.9	0.127	0.750	
1-1	3/29/72	1	8.62	46.1	13.8	0.206	0.661	35
1-1	3/29/72	2	8.75	45.6	14.6	0.200	0.685	37
1-1	3/31/72	1	9.35	46.5	14.8	-	0.678	39
1-1	3/31/72	2	9.05	46.6	14.8	-	0.678	37
1-1	4/3/72	1	9.98	49.2	12.1	0.221	0.679	85
1-1	4/3/72	2	9.44	43.5	13.7	-	0.679	91
	Average		9.20	46.2	13.9	3.209	0.677	
1-2	4/7/72	1	11.98	58.6	10.5	0.295	0.675	116
1-2	4/10/72	1	13.61	41.6	13.3	0.289	0.675	114
1-2	4/10/72	2	12.68	42.4	14.5	0.256	0.675	104
1-2	4/11/72	1	13.12	44.6	12.8	-	0.674	109
	Average		12.85	46.8	12.8	0.280	0.675	
2-2	4/17/72	1	11.91	80.7	9.4	0.226	0.757	46
2-2	4/17/72	2	12.16	85.3	9.3	0.182	0.756	55
2-2	4/18/72	1	13.28	95.0	6.9	0.177	0.756	101
2-2	4/18/72	2	13.34	94.7	6.6	-	0.756	104
2-2	4/18/72	3	12.35	93.4	7.1	-	0.756	96
	Average		12.61	89.8	7.9	0.195	0.756	
1-3	4/27/72	2	12.56	39.6	11.1	0.196	0.719	91
1-3	4/28/72	1	13.69	35.6	11.7	0.176	0.733	97
1-3	4/28/72	2	13.34	32.3	11.7	0.190	0.733	106
1-3	5/1/72	1	13.03	36.1	10.8	-	0.733	118
1-3	5/1/72	2	12.88	35.3	11.6	-	0.733	111
	Average		13.10	35.8	11.4	0.187	0.730	

TABLE 9. EXPERIMENTAL 13-MODE PROCEDURE
DRY CORRECTED EMISSION RESULTS (Cont'd)

Engine	Date	Run	Grams/Bhp-Hr. HC	CO	NO_x Obs.	Aldc.	Cycle Weighted BSFC	Humidity gr/lb d.a.
3-3	5/11/72	1	10.27	28.4	10.5	0.272	0.655	98
3-3	5/15/72	1	8.41	30.1	11.3	0.254	0.614	80
3-3	5/16/72	1	8.73	29.6	10.3	0.261	0.630	101
3-3	5/16/72	2	8.19	33.2	10.7	-	0.620	95
3-3	5/17/72	1	9.37	27.9	10.7	-	0.642	92
3-3	5/17/72	2	9.41	33.1	10.6	0.259	0.627	98
	Average		9.06	30.4	10.7	0.262	0.631	

said regarding the results other than the revised experimental procedure was operable and acceptable data was obtained.

(b) Engine 1-1: Testing of engine 1-1 was begun on March 21, 1972 by running the nine-mode tests. A full break-in was not required on this engine because it had been used previously by the manufacturer for emission test purposes. A short run of about 8 hours, however, was made to make sure everything was in order before testing began. Timing and idle speed were adjusted as specified to 6° BTDC at 600 rpm. Three nine-mode runs were made with fair repeatability and no problems were encountered.

Further testing of engine 1-1 utilizing the experimental 23-mode procedure was begun on March 29, 1972. As noted in a letter dated April 7, 1972, to the Project Officer, Mr. John McFadden, the low rpm portion of the 23-mode cycle was performed at 1300 rpm instead of 1200 rpm, because the engine would not hold steady loads at high power levels at the 1200 rpm speed. There was no appreciable vibration or noticeable malfunction of the engine i. e. misfiring, surging, etc. and no explanation can be offered at this time as to the difficulty encountered.

Although the overall brake specific results in Table 9 were repeatable from run-to-run, the individual mode repeatability was sometimes much less than the summary table would indicate. It was felt that this may be due to this specific engine, however, whatever the reason, we were concerned about some of the mode-to-mode agreement for this engine. This phenomenon is expected during certain modes i. e. C, T, and idle, and light loads, especially at low speed. These modes have always been difficult to run and obtain highly repeatable values, ± 5 percent of the mean for example.

(c) Engine 1-2: After a short run-in, similar to engine 1-1, testing of engine 1-2 began on April 6, 1972. The nine-mode runs went smoothly with no problems. Summary Tables 7 and 8 show good repeatability for both the Federal Test Procedure concentration and mass results. Run 2 NO and NO_2 were low and Run 4 HC was high, but investigation has shown the runs were made properly and the values represent actual engine operation at that time and not a chart reading error or computation error.

The usual mode-to-mode variability of certain modes of the 23-mode procedure were experienced. When the calculations were made of the run composite, the variations in mode concentrations apparently have a self-compensating effect so that cycle results are quite comparable.

(d) Engine 2-2: Baseline runs for engine 2-2 began with the nine-mode test procedure on April 14, 1972. The three runs used went smoothly with no problems. The major point of interest with the 23-mode test was the difference in emission levels on different days. During a single day the mode-to-mode repeatability was good but the gross difference in weather between the 17th and 18th of April are felt to have influenced the emission levels of

the engine. Both changes in barometer and inlet air humidity were significant as a result of a cold front.

On mode 13, the maximum power, 2500 rpm condition, CO went off scale and was greater than 11 percent full scale of the instrument. This occurred during each test. Since the instrument is routinely spanned to 11 percent CO at 100 percent chart deflection, this value was entered for the CO. Mode-to-mode repeatability appeared good for all the tests run including aldehydes which were more repeatable than usual.

(e) Engine 1-3: Testing of engine 1-3 began on April 14, 1972 when the nine-mode FTP tests were begun. The results were quite repeatable. The 23-mode results per Table 9 also show good repeatability on a run-to-run basis. The computer print-outs of the various tests did not show a good modal repeatability as the run-to-run results might have indicated. Several modes of the nine-mode tests look suspicious and steps were taken to check the strip charts for possible errors in reading.

The 23-mode results were acceptable on a mode-to-mode basis although some strange points were evident. Specifically, Run 2 on April 27, 1972, shows modes 9 and 14 (the 92 percent power modes) to have very high CO concentrations. This has happened before, with engine 1-2 made by the same manufacturer, and is felt to represent a transition point on the carburetor. Several times the various emissions would exhibit a string of high or low readings on a particular run. This is felt to represent actual engine performance as no errors were made in reading the emission levels.

(f) Engine 2-3: The nine-mode testing of engine 2-3 began on May 12, 1972 with no problems. The run-to-run repeatability was very good. The modal repeatability was felt to be satisfactory also. The overall 23-mode results also showed good run-to-run repeatability as seen in Table 9. The computer print-out sheets showed good modal repeatability as well. As with all the engines tested, the modal repeatability was not as good as the run-to-run repeatability on this engine, and also as usual, aldehyde measurement showed more variability than the other emission measurements.

4. Comparison of Nine-Mode and 23-Mode Emissions

Table 10 is a comparison of the average results obtained by the nine-mode and 23-mode test procedures for the six baseline engines. To facilitate the comparison, a comparison ratio (CR) was computed by dividing the 23-mode by the nine-mode brake specific emission rates. CR values greater than one indicate the 23 mode results were greater than the nine-mode. From Table 10, HC ratios ranged from 1.8 to 3.3, CO ratios ranged from 0.97 to 3.2 while NO_x ratios varied from 0.77 to 0.96. Although the two procedures result in essentially equivalent NO_x, the CO and HC range of variation does not justify direct comparison of the procedures.

TABLE 10. COMPARISON OF AVERAGE NINE-MODE AND 23 MODE RESULTS
Six Engine Baseline

Engine Code	Brake Specific Emission Rates, Grams per bhp-hour HC 9 Mode	HC 23 Mode	HC CR	CO 9 Mode	CO 23 Mode	CO CR	NO_x 9 Mode	NO_x 23 Mode	NO_x CR
2-1	3.15	10.05	3.3	14.77	47.8	3.2	14.48	11.92	0.82
1-1	3.07	9.20	3.0	18.27	46.2	2.5	14.42	13.94	0.96
1-2	7.33	12.85	1.8	32.6	46.8	1.4	14.00	12.78	0.91
2-2	8.70	12.61	2.2	69.2	89.8	1.3	10.11	7.87	0.77
1-3	4.53	13.10	2.9	15.8	35.8	2.3	12.22	11.38	0.93
2-3	3.36	9.06	2.7	31.4	30.4	0.97	11.20	10.69	0.98

Several other analyses were made to establish correlation between the two procedures with inconsistent results. No clear cut trends of agreement between procedures or prediction of say 23 mode from nine-mode results was evident from the data for the six 1972 baseline engines. Although beyond the scope of this project, there are probably several good reasons for this difference. One likely reason for the higher HC by the 23 mode test was the use of a lightly heated (160°F) FID for analysis instead of the NDIR sensitized to a paraffin, n hexane, used in the nine-mode. A factor of 1.8 is used in the mass calculation of nine-mode HC concentrations to compensate for this difference. The lightly heated FID also eliminates the cold trap required for NDIR analysis, where some HCs are lost.

One obvious reason for higher CO by the 23 mode procedure is that several high power conditions are included in the 23 mode that are not in the nine-mode schedule. These conditions, all typically at intake manifold vacuums less than 2.5 in. Hg. (adjacent to and including WOT operation), are producers of substantial quantities of CO. A third possible reason for the lack of agreement in HC and CO may be the large number of modes and weighting factors used in the 23 mode test relative to the nine-mode procedure. The origin of the 23 mode test schedule operating speeds, loads, and weighting factors was from a computer analysis of the original 1961 Ethyl truck and bus survey data. The computer analysis and subsequent formulation of the test schedule was performed by EPA's Procedural Development Branch, Division of Emission Control Technology.

The nine-mode test procedure was reportedly arrived at by the State of California Motor Vehicle Pollution Control Board, now known as the Air Resources Board, in conjunction with the Automobile Manufacturers Association and certain gasoline truck manufacturers. A direct comparison of the modes and weighting factors is not obvious. While the specific origin of and basis for the 23 mode test is known, the nine-mode procedure is mostly unknown. Although both procedures are engine exercises, the nine-mode test is recognized as much easier to design around than the 23 mode

test. Neither include transients (acceleration-deceleration) and this is a shortcoming of simplistic engine speed-load emissions mapping procedures.

5. Computer Print-out of Modal Data

Appendixes A through F to this report contain computer print-outs for every run summarized in Tables 7, 8 and 9. One appendix is devoted to the baseline results for each engine and follows the chronological schedule of test, i.e., engine 2-1 is covered by Appendix A while Appendix F contains data for the last engine tested, number 2-3. Each appendix is subdivided into three sections, the first containing nine-mode concentrations, the middle section the California calculation of the nine-mode test in mass per bhp-hour, and the final section listing all the 23-mode run data obtained. To find a specific print-out for a given engine, locate the proper section of the respective appendix and then match up date and run number to that listed in the test summary table.

There is a substantial amount of data in these six appendices starting with raw, as-measured concentrations and ending up with weighted modal results. There are many ways this data may be useful and accordingly, full details are shown. For some print-outs, such as the Federal FTP mass and the 23 mode test, engine operating parameters of observed flywheel hp, fuel consumption, intake manifold vacuum are listed.

In the case of the 23-mode, grams of emissions per hour, are computed and shown. This is the best method for expression of mass rate for all modes. A cycle weighted brake specific fuel consumption (BSFC) is shown based on modal fuel and power readings. The same weighting factors used for emissions were used for BSFC. Modal air-fuel ratio was calculated and printed by the computer for Engine 2-3. The reader is referred to Appendixes A through F for the full data and particulars regarding the baseline test series.

B. Control Technology Assessement

The intent of the control technology phase of this project was not one of design and development, rather of screening, confirmation, evaluation and assessment both of laboratory run experiments at SwRI and data available from the manufacturer. In addition to the meetings held on January 13 and 14, 1972, with the two manufacturers, two additional separate meetings were held on March 7 and 15, 1972.

The specific objective of these meetings was to obtain advice and as many devices and equipment, parts, ideas, etc., as possible to make the in-depth study of future control technology as meaningful as possible. Some of the specific methods discussed were:

Exhaust Gas Recirculation (EGR) Internal-External
Spark Retard plus Oxidation Catalyst
Spark Retard plus Manifold Reactor
Lower Compression Ratio (add head gaskets)
Derate Engine by Using Smaller Carburetor
Electronic Fuel Injection (Open-Closed)
Capacitor Discharge Ignition
Variable Venturi Carburetor

Of course, there are many other possibilities and not all items on the above list were to be accommodated within the time and money constraints of the project. For example, electronic fuel injection holds promise, but requires development. Capacitor discharge will do little to reduce emissions from a new engine, but should go far in maintaining low emissions due to the improved durability of the equipment and lack of wear, etc.

Little in the way of data or experience was provided by the manufacturers with regard to achieving substantial improvements in emissions from their engines. The discussions also covered the usual concern about the relationship of laboratory engine results to driveability and durability. It was emphasized that this control technology project had to begin with laboratory studies which would have to be followed by studies of other aspects.

From the control technology standpoint and the availability of test results, etc., the meetings were not nearly as productive as hoped. Little was offered in the way of assistance by one manufacturer and only limited assistance was promised by the other. The representatives of both companies were sincere in wanting to be of help, but, since their major concern was passenger cars, they plainly could not offer much at that time in the program.

The general lack of technology in the industry required Swift to respond quickly with control approaches that required little or no design and development. Within the desired time constraints, this limited the items for test to those normally used for light duty engines, such as oxidation catalysts, EGR, manifold air injection, etc. As soon as the full impact of these findings with the manufacturer was felt, the staff of the Emissions Research Laboratory, on the advice and consent of the Project Officer, began a series of contacts with the control equipment supply industry. Manufacturers and suppliers of EGR valves and control equipment, oxidation catalysts, oxidation-reduction catalysts, fuel injection systems, and turbochargers were contacted and where available samples obtained for consideration.

The time constraints of the project precluded the operation of many items since additional development would be necessary to adapt most of these components to the engine. Essentially no time or effort was available for such studies and optimization so that of all the items considered, only a

popularly-used commercially-available precious metal type oxidation catalyst was selected for evaluation. A pair of platinum-type honeycomb catalytic reactors, as well as technical information and support, were obtained from the reactor manufacturer. These reactors were of a size that could be used with both control technology engines.

1. Engine Z-3 Control Technology Results

Conversations with the Project Officer on April 28, 1972, resulted in the test plan shown on Table II for the control technology assessment of engine Z-3. The test plan was not considered a rigorous parametric study in the classical sense in that one parameter is not always varied over the entire range of conditions at a time to determine effects singly. Engine timing experiments, Step 1, were parametric in nature as was Step 5. Only one catalyst and one air pump system were considered. Clearly, there were too many dimensions of possible interest to investigate each singly, much less in all the possible combinations and permutations to meet the time and financial constraints of the project.

The plan was to explore possibilities of gross emission effects due to gross changes in engine operation. This approach was somewhat unconventional, but with only two months to complete the tests with engine Z-3, there was no alternative. As specified by the Project Officer, the experimental 23-mode test procedure was the primary basis for comparison of HC, CO, and NO_x emissions performance. A shortened version of this procedure was used in which mode times were reduced to approximately 1.5 minutes. This is sufficient time to obtain stable engine and emissions performance under most all operating modes.

(a) 1972 Versus 1973 Version Tests -

Prior to starting Step 1, the engine was operated in its 1973 California version with a different distributor, carburetor, carburetor air cleaner assembly and water thermostat. These items were furnished by the manufacturer and their installation and adjustment specifications strictly adhered to. Repeated 23-mode runs were made with the 1973 version of the engine with emission rates of CO substantially higher and NO_x substantially lower than the 1972 basic engine. These results are summarized below and the computer run sheets included in Appendix G.

Engine Z-3, Experimental 23 Mode Mass Emission Rates, grams per bhp-hr (Army Laboratory)

	CO	HC	NO_x
1972 Baseline Engine	30.4	9.06	10.69
1973 California Configuration	70.77	10.09	5.82
1972 Engine (Retest)	33.37	8.54	11.57

TABLE II. PLAN OF TEST, ENGINE Z-1

Step	Description
1	Convert Engine to 1973 California version and very basic timing, i.e., say 10° and 5° advanced, standard and 5° and 10° retarded timing.
2	Install larger and smaller carburetor jets to modify engine air-fuel ratio at standard timing.
3	Install air pump system and run engine at standard timing and one extreme each side of standard.
4	Install standard EGR system and run at standard timing and one extreme advanced and retarded timing. Use standard engine with the air pump off.
5	Investigate modified EGR, i.e., other flow rates at various modes.
6	Install catalytic reactors, clean fuel system, and run with and without air pump at standard timing advanced and/or retarded (operate on clear fuel unleaded) run longer modes and sample exhaust before and after catalysts.
7	Carburetor modification - derate engine by running with two large barrels of 4 barrel carburetor blocked. Standard engine otherwise.
8	Combine best EGR with best air pump - catalyst-ignition timing found in Steps 3, 5, and 4.
9	Investigate other combinations of the above or control approaches as they develop.

The higher CO and lower NO_x with the 1973 engine on the 23-mode test are unexplained although the run-to-run agreement for each series of tests was satisfactory and the changes were real. Several runs were made with the engine returned to its 1972 standard configuration to verify the large differences in CO and NO_x. The baseline (six tests) and retest data were in agreement.

Although the 23-mode test schedule was established by the Project Officer as the test procedure for use in control technology assessment, it was felt of interest to determine what the engine would emit on the nine-mode schedule both in concentration by the current FTP and in mass by the 1974

FTP. It is the latter which applies to gasoline engines in heavy duty service in California beginning in 1973 and nationwide beginning in 1974. These results are summarized below:

Engine 2-3, Nine-Mode FTP Concentration Results

	HC, ppm n Hex.	CO, %	NO^*, ppm
1972 Standard Engine (Baseline)	116	0.66	1601
1973 California Configuration	88	0.78	971

*Corrected to 75 grains humidity

Engine 2-3, Nine-Mode 1974 FTP Mass Results, grams/bhp-hr

	CO	HC	NO_x*	HC + NO_x
1972 Standard Engine	31.4	3.26	11.20	14.56
1973 California Configuration	33.73	2.57	6.59	9.15

*Corrected to 75 grains humidity

Based on the nine-mode schedule, the difference in emissions between the 1973 and 1972 engines were much less than earlier shown on the 23-mode except in NO_x. The only good explanation is that an engine calibrated for a schedule incorporating only six different modes (nine-mode FTP) may result in a quite different conclusion if operated on a schedule comprising many more modes such as the 23-mode schedule where 21 different modes are employed. Note, only 15 different modes are used in the calculations since some modes had a zero weighting factor. Of course, weighting factors, choice of power levels and, to a much lesser extent, engine rpm play important parts in establishing an engine's total emission rate.

It may be noted that the 1973 California configuration brought the engine's HC+NO_x well below the 1973 California and 1974 Federal limit of 16 grams per bhp-hr without materially changing CO which was below the 1973 limit of 40 grams per bhp-hour. To this end, the 1973 version is considered an improvement over the 1972 engine. The 23-mode procedure, an experimental method, yields a much different conclusion in terms of CO and NO_x. Run data for this series of tests are included in Appendix G of this report for further analysis on a mode-by-mode basis, etc. The conclusion from this series of tests was to utilize the 1972 standard engine as the basis for control technology assessment. In effect, these experiments indicate that changing back from 1973 to 1972 would be an important improvement in exhaust pollution from this engine, based on the 23-mode tests.

The arrangements for use of Cell 3 of the U. S. Army Fuels and Lubricants Laboratory called for release of this facility on June 1, 1972. Accordingly, the test efforts were transferred to the Emissions Laboratory on June 1, but not before all items of equipment, dynamometer, etc., were checked and recalibrated. Power curves were run at several speeds with engine 2-3 to ensure the new facility dynamometer power and speed read-outs would be identical to that previously used. After several days of work, the physical installation was completed and the dynamometer in operation. Power, speed, fuel, manifold vacuum and other physical operating characteristics were replicated and operation of the engine was found to be essentially identical to the previous location.

Before continuing with the control technology phase of the project, several more days were used to rerun the 1972 and 1973 engine version 23-mode tests discussed earlier. These results are summarized below and show close to the same magnitude of difference between 1972 and 1973 engines.

Engine 2-3. Experimental 23 Mode Mass Emission Rates, grams per bhp-hr (Emissions Laboratory)

	CO	HC	NO_x
1972 Baseline Engine	86.20	7.01	5.60
1973 California Configuration	72.40	8.22	6.61

The 1973 version of the engine repeated the tests made earlier in the Army Laboratory with CO 72.4 versus 70.77, HC 8.22 versus 10.09 and NO_x 6.61 versus 5.82. Trendwise the 1972 engine was still better than the 1973 engine per the 23-mode test, but the 1972 engine data were not as close to earlier 1972 data as desired.

The same instruments, sampling system and fairly similar exhaust piping, muffler, etc., were used. The same emissions test fuel, exhaust restriction and calibration, span and zero gases were used. The engine was not damaged or altered in making the move and to date, no really good explanation for the differences in 1972 emission rates has been found.

In the last part of Appendix G may be found the 23-mode computer print-out sheets. Comparing the modal data for these runs against that from the earlier data, also in Appendix G, obtained in the original installation, reveals that the differences are predominately in the light load portion of the schedule. This is, of course, one of the big contributors of HC and is the most difficult part of the 23-mode schedule to operate.

In summary, no really satisfactory explanation of the difference in Army Lab 1972 and Emissions Lab 1972 data could be found. The good repeatability for the 1973 version of the engine indicates that the test location, procedure, etc., was not necessarily the cause.

(b) Step 1 - Effect of Timing

The intent of this series was to determine what effect gross changes in basic engine spark timing would have on emissions and performance. In running these tests, the 1972 engine was used and the basic distributor timing set at 28° BTDC, 16°BTDC, standard timing (4°BTDC), 4°ATDC and 12°ATDC. The results are summarized on Figure 5 and are 23-mode composite data on a grams per bhp-hour basis. Setting the timing later and later resulted in a nearly uniform decrease in NO_x, the greatest reduction occurring between 16°BTDC and 4°ATDC. This same range had the opposite effect on CO, however, with about a 35 percent increase in CO between 16°BTDC and 4°ATDC range.

HC increased greatly between 4°ATDC and 12°ATDC indicating a loss in combustion efficiency. Settings of 28°BTDC and 12°ATDC represent the approximate advance and retard limits of the engine as far as engine operation was concerned. Cycle weighted BSFC is also plotted on Figure 7 as an indication of the effect of timing on fuel consumption and economy. Note the effect of retarded timing on cycle BSFC with a significant loss in economy of operation shown at 4 and 12°ATDC.

Appendix H contains tabular, computer print-out, data for modal analysis and plots of the data. Figures H-1, H-2, and H-3 show the effect of power on the mass rate, grams per hour for HC, CO and NO_x as NO_2. Also plotted are the 1973 California configuration modal results (from data in Appendix G) for comparison to the 1972 standard engine. By oversight, one run at 12°ATDC was made with the distributor vacuum advance line disconnected. The run was valid otherwise and the results are plotted for general information. Both 1200 rpm, broken line, and 2500 rpm, solid line data are plotted. Also shown are closed throttle (CT) and idle results.

Figures H-4 and H-5 of Appendix H are similar plots of engine intake manifold vacuum and fuel consumption. Other plots of the data in the Appendix H computer print-outs could be made such as power versus emissions on a brake specific or concentration basis. Plots of air-fuel ratio versus certain of the emissions would also be informative. In summary, retarding the spark 4 to 8 degrees from manufacturers standard timing of 4° BTDC would reduce both HC and NO_x with an increase in CO. Assuming performance is not jeopardized too much, this might be considered in conjunction with other approaches, especially one that reduces CO.

The importance of the closed throttle mode on HC production and its effect on the 23-mode result is dramatic. The two closed throttles are given 18 percent of the weight (12 percent at 2500 rpm and 6 percent at 1200 rpm). Any device or approach that can substantially reduce concentrations, nominally 30,000 to 90,000 ppmC, during these modes can have a noticeable influence on the final results.

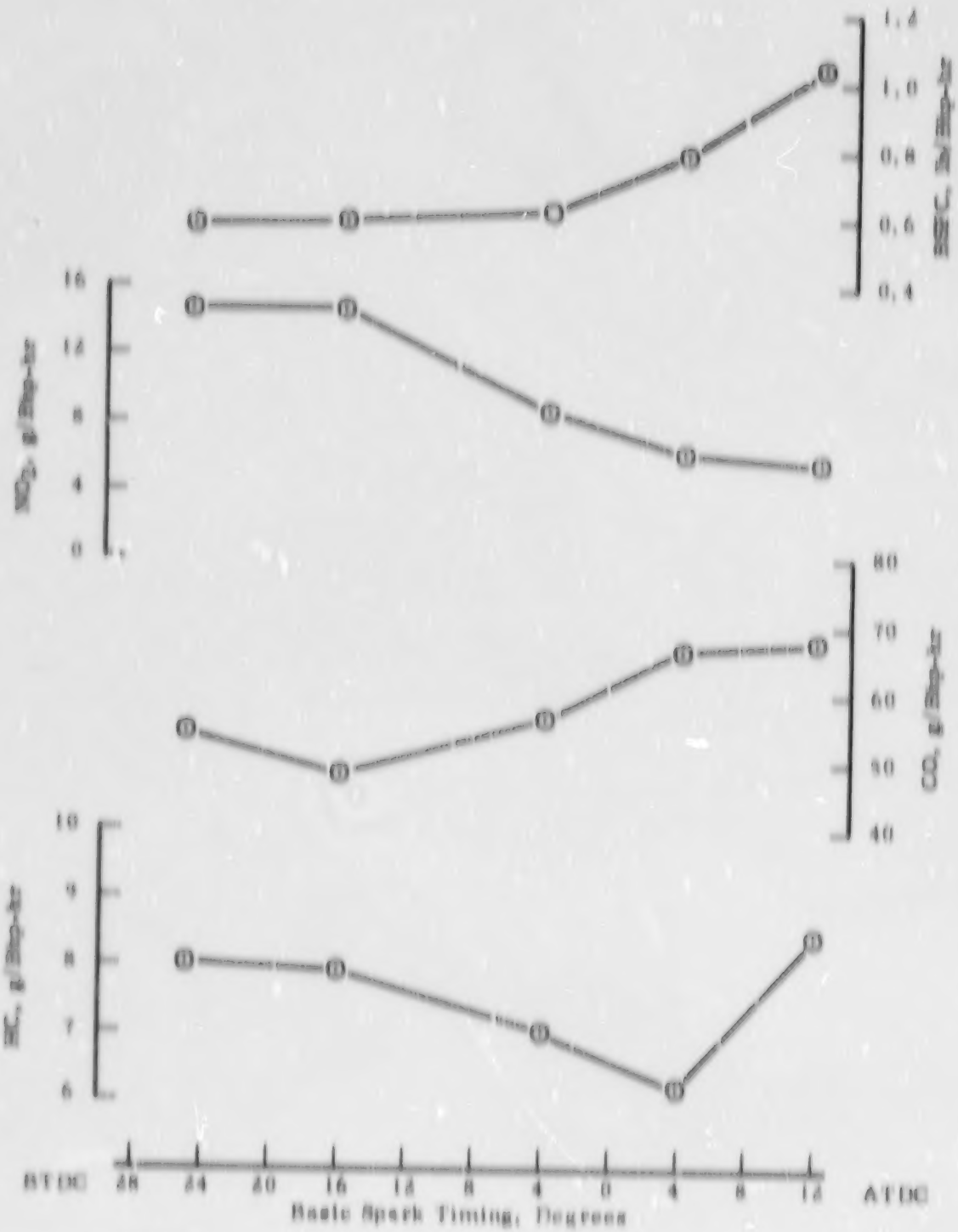


FIGURE 5. EFFECT OF SPARK TIMING ON EMISSIONS ENGINE 2-3, 23 MODE TEST

(c) Step 2 - Effect of Air-Fuel Ratio

The usual way to investigate the effect of air-fuel ratio is to run tests with the main metering system modified to admit more or less fuel for a given air flow requirement. Several main metering jet and metering rod combinations shown in Figure 6 were furnished by the manufacturer and experimented with. The air-fuel ratio was determined for each of the 23 modes using the "Spindt Method" of calculation. From the modal air-fuel ratios, an overall "weighted air-fuel ratio" for the entire 23-mode test was computed using the modal weighting factors.

Figure 7 is a summary plot of the 23-mode results with the various jet-rod combinations. Also shown are the various size jets that were larger or smaller than the standard 0.073 inch jet, 0.0368 inch rod, combination. Note the plots of NO_x, CO and HC show that the mixture has an important effect on emissions. The trends of lower NO_x and higher HC and CO as air-fuel mixture becomes richer with fuel was as expected. The dramatic increase in CO was not unexpected based on our experience with a number of in-service gasoline trucks. On the fuel lean side, the 1972 engine was not too far from its "lean limit" as noted by the attempted operation of the engine with very small jets (0.064 inch). Weighted BSFC seemed little affected by the change in air-fuel ratio except at the rich mixtures.

Appendix I contains the computer sheets listing the modal results for this series of experiments. The gram per hour emission rate has been plotted against percent power for the several modes included in the 23-mode test. Grams per hour was selected as the primary expression since all modes have such a rate. Grams per bhp-hour is not applicable or appropriate where no usable load is obtained as in idle, closed throttle and very light load, i.e., 0-2 percent power. Concentration results, on the other hand, may be misleading since they do not include the air flow and thereby lack the direct contribution to the cycle result where mass rate is important.

Appendix Figures I-1, I-2, and I-3 portray HC, CO and NO_x as NO_2 in this way and are similar in appearance, but not in trend, to those in Appendix II for the effect of timing. Figures I-4 and I-5 show manifold vacuum and fuel consumption as a function of the power output. Time has not permitted further graphing and analysis of the results, although more could be done in this regard. In summary, this series of experiments confirmed the effect of air-fuel ratio on carbureted gasoline engines; namely, that richening the mixture with fuel reduces NO_x at the great expense of increasing CO and HC, as well as fuel consumption. As with the study of spark timing, this is another item which should be considered with after-treatment approaches such as air injection with or without catalysis.

(d) Step 3 - Effect of Exhaust Manifold Air Injection

Engine 2-3 was fitted with the factory exhaust manifold reaction

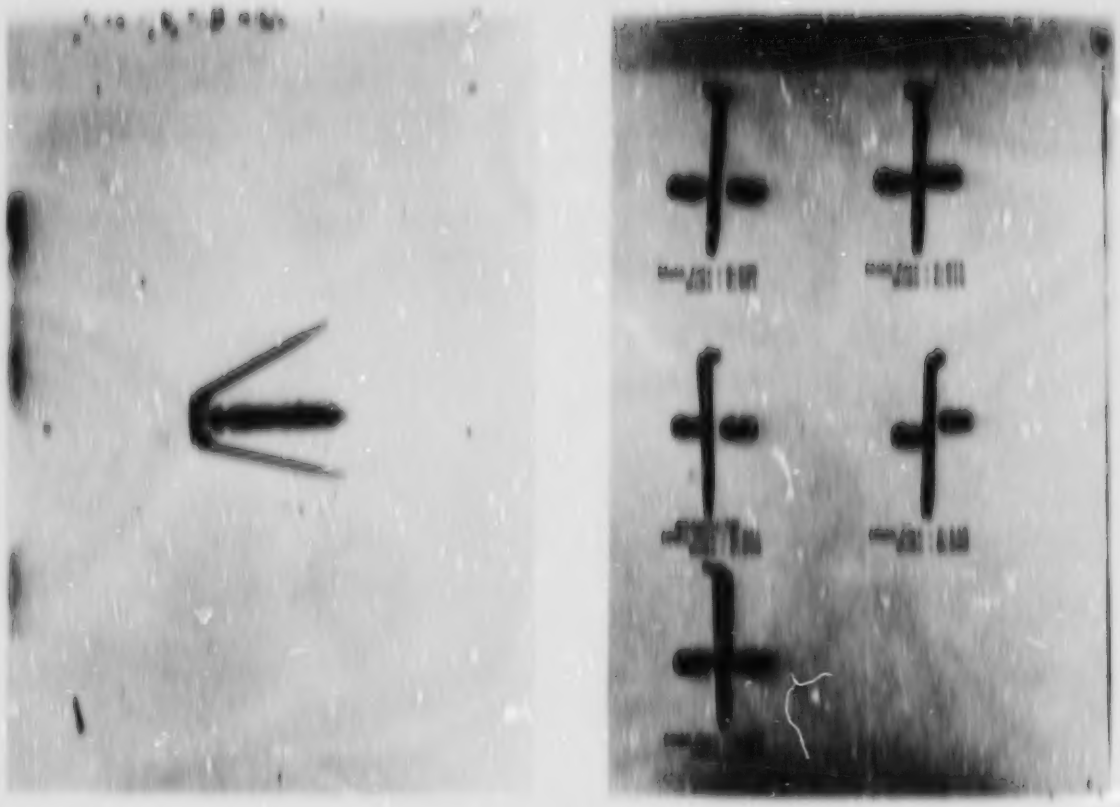


FIGURE 6. CARBURETOR RODS, JETS, AND THEIR LOCATION (ENGINE 2-3)

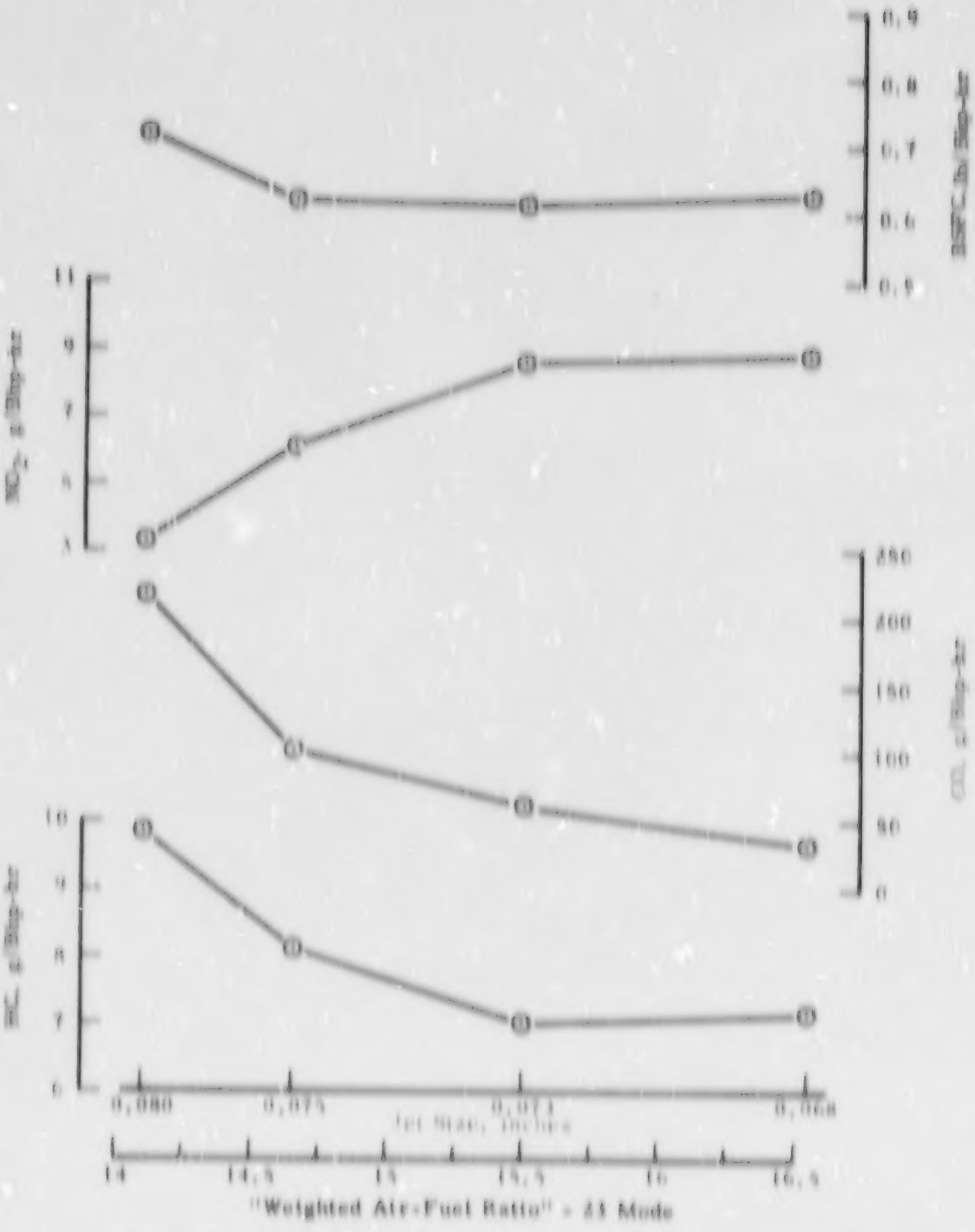


FIGURE 7. EFFECT OF AIR-FUEL RATIO ON EMISSIONS ENGINE 5-5, 13 MODE TEST

equipment, as shown in Figure 8. This involved replacing exhaust manifolds and installing air pump, belt, pulleys and required lines, fittings and injection tubes, so that air is admitted on the exhaust valve tulip. Several 23-mode runs were made at various basic injection timing settings including standard (4°BTDC), advanced settings of 16 and 28°BTDC and a retarded setting of 4°ATDC. The computer print-outs for this series of tests are included as Appendix J.

The grams per bhp-hr 23-mode results for HC, CO and NO_x and weighted BSFC are depicted on Figure 9. Also shown are the standard engine emissions versus timing for comparison. The brake specific NO_x emission values show little variation with timing that are not due to timing alone. And, relative to the engine run without air, the influence of air injection on HC is somewhat disappointing. Air injection did seem to reduce CO, however, especially at the standard 4°BTDC and at 4°ATDC.

Part of the explanation may lie in the large weighting given idle, closed throttle and light loads where exhaust oxidation would have a limited effect. Recall that the air injection acts as a diluent as well as a source for oxygen and that the diluent effect, which reduces concentrations, does not reduce emissions on a mass basis. Appendix J contains modal plots, Figures J-1 through J-5, of the run results for HC, CO, and NO_x, manifold vacuum and fuel consumption as a function of power level. Please refer to these plots for further insight on the effect of exhaust manifold oxidation by injected air.

(e) Step 4 - Effect of Light Duty EGR System on Emissions

This series of experiments required an experimental intake manifold furnished by the manufacturer that had been machined and prepared for exhaust gas recirculation from the exhaust heat crossover back to a central point in the intake manifold directly below the carburetor. The EGR is routed completely internal within the intake manifold and all that shows is a valve and the valve control vacuum hose that connects to the distributor vacuum line. Photographs of this system are shown in Figure 10. The system as used was the same as used in light duty vehicles and was installed and operated according to manufacturer's recommendations. The EGR rate was essentially zero, from 0 to 2 inches intake vacuum and constant at approximately 1 lb per minute above 8 inches of vacuum. The EGR rate increased in a nearly linear fashion between 2 and 8 inches of H_2O vacuum.

As with other similar studies, a series of 23-mode experiments was made at basic timing of 28, 16, and 4 (standard) °BTDC and 4°ATDC. The 23-mode composite results are also plotted on Figure 9 along with the standard engine without light duty EGR for comparison. Note that EGR is most effective on reducing NO_x at advanced settings where maximum NO_x was produced. To optimize the EGR as far as basic timing is concerned, it seems that a 4°ATDC or 8° retard from standard, results in the lowest

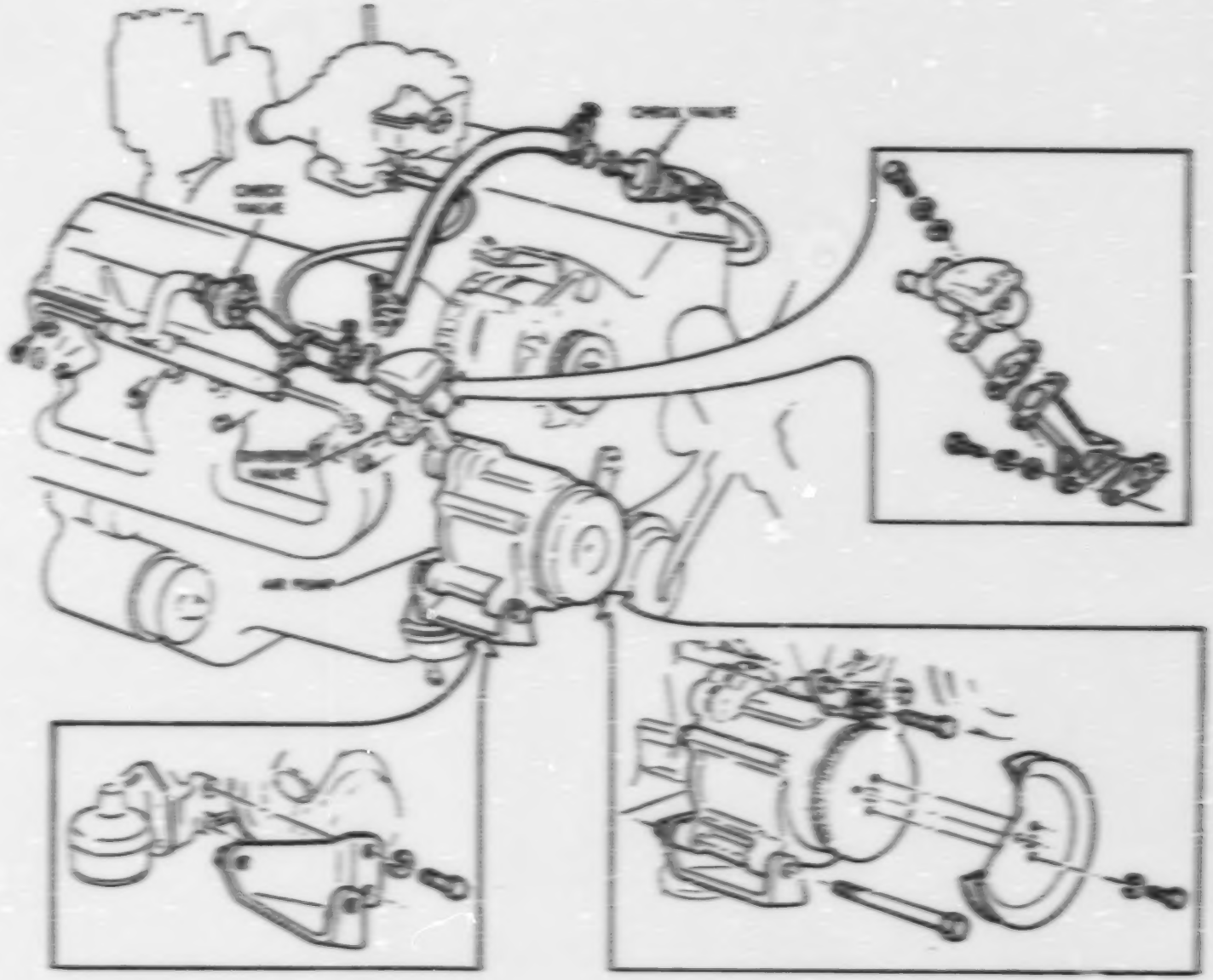


FIGURE 6. EXHAUST MANIFOLD AIR INJECTION EQUIPMENT

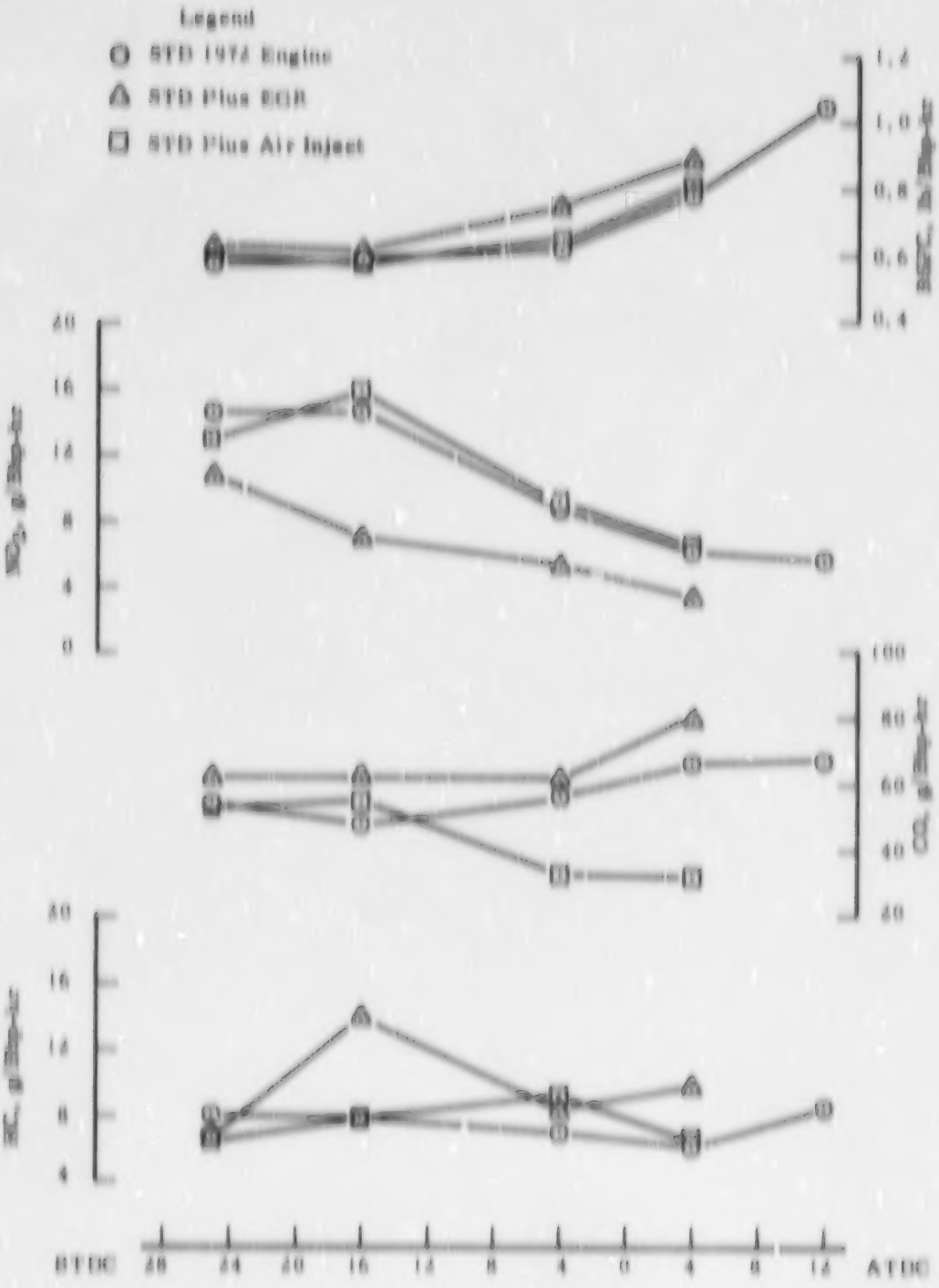


FIGURE 9. EFFECT OF LIGHT DUTY EGR AND AIR INJECTION ON EMISSIONS, ENGINE 5-1, 53 MODE TEST

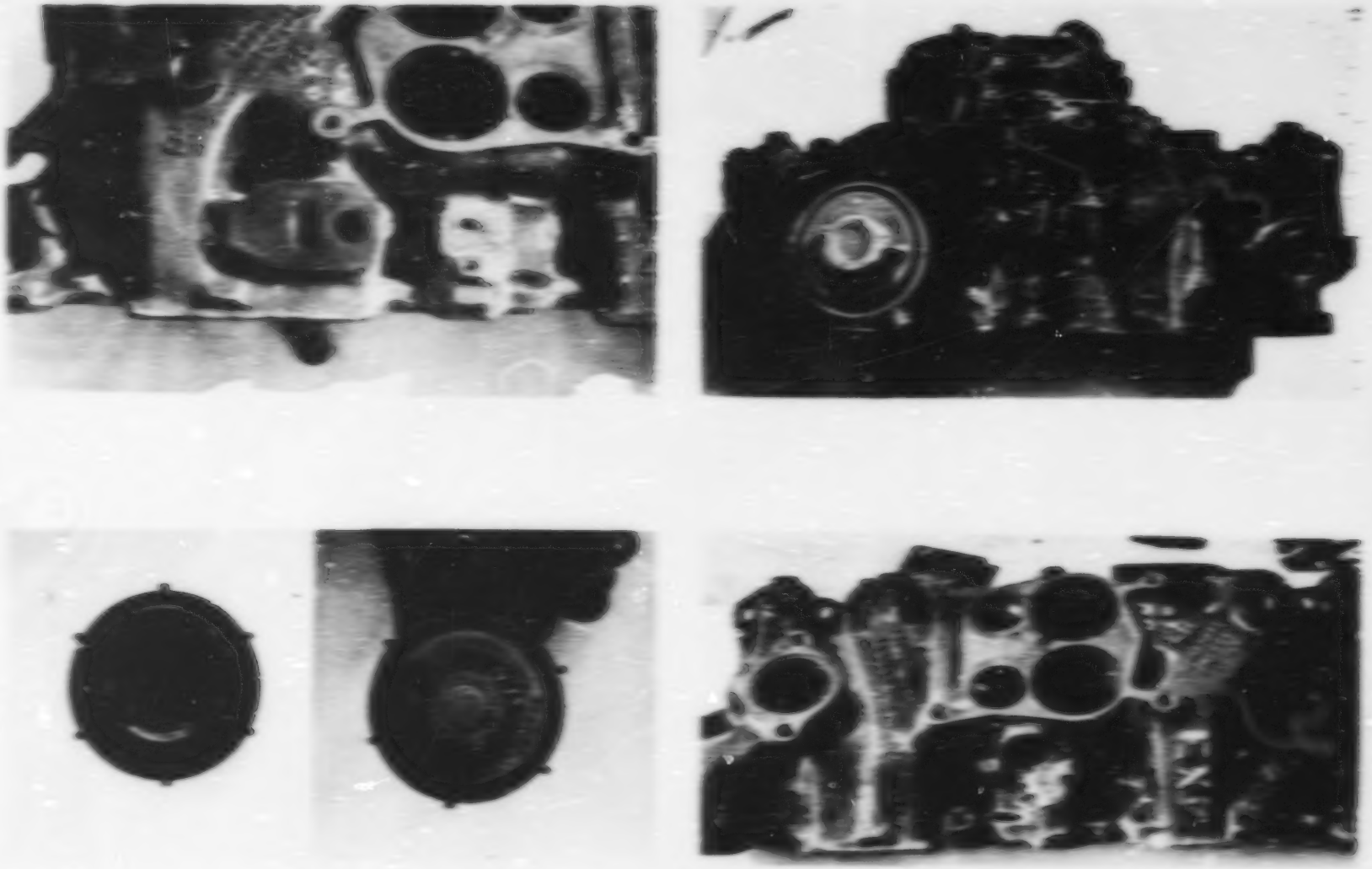


FIGURE 10. LIGHT DUTY EGR EQUIPMENT

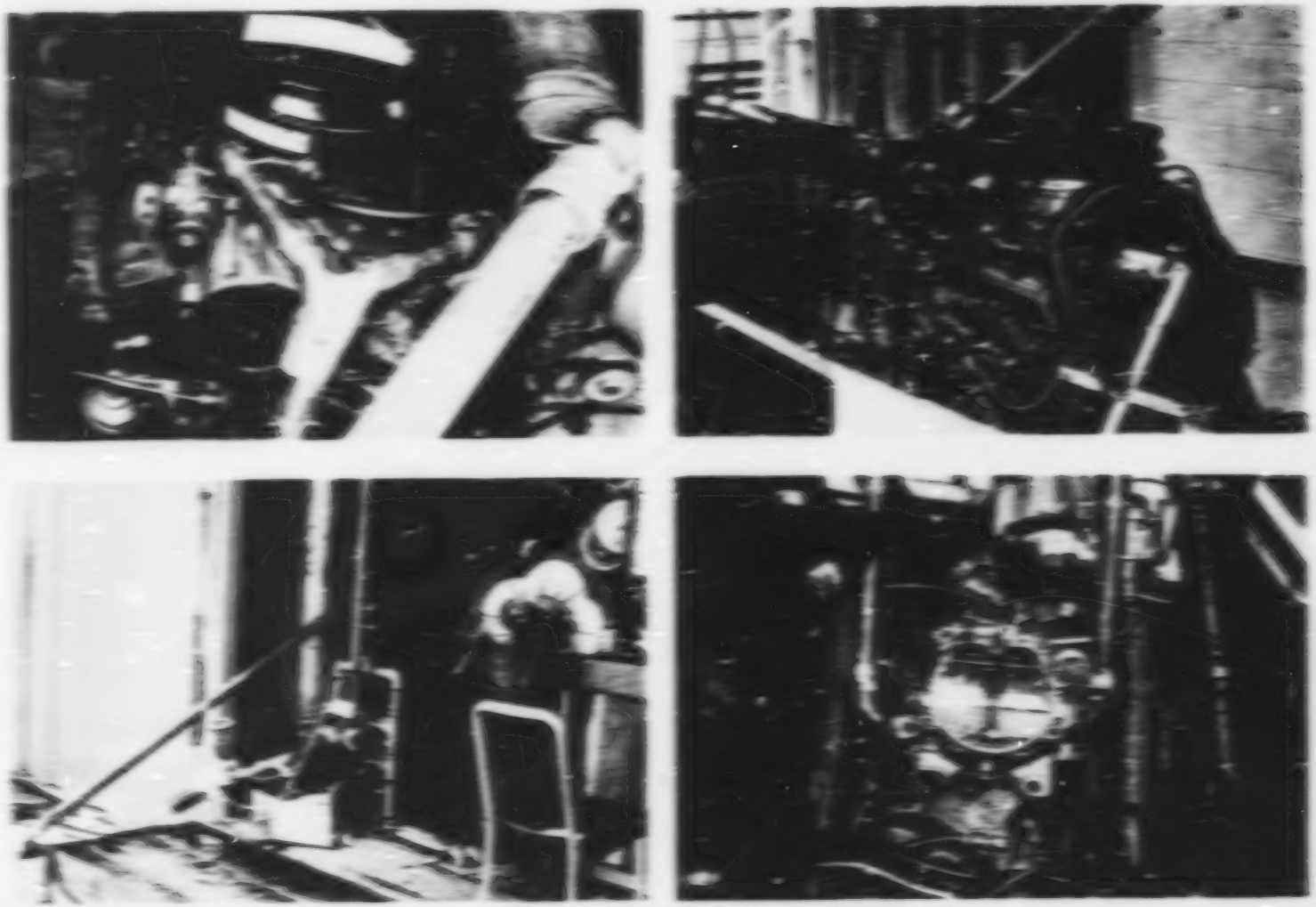


FIGURE 11. LABORATORY EGR SYSTEM

NO_x of about 4 grams per bhp-hr.

This is not necessarily the best operating point for CO, however, as shown on Figure 9, since this gives the maximum CO. HC, like CO, was adversely affected, i.e., increased by EGR throughout the range of timing studied, and , like CO, 4° ATDC was not the best setting for HC. It may be that in combination with other control approaches, the 4°ATDC will emerge as a possible operating point.

Appendix K contains the tabular computer print-out sheets and graphed results on a modal basis for the series of tests on the light duty EGR system. Please refer to these for additional detail or if a more thorough analysis is desired.

(f) Step 5 - Effect of Laboratory EGR on Emissions

This step was originally intended to involve tests at a given basic timing, such as standard, with a flow of exhaust modified from the light duty flow schedule. The light duty valve recirculates exhaust based on signal pressure from the distributor manifold vacuum line. On inspection of the flow capacity, it was found that even operating at maximum signal pressure the EGR rate would not give the desired flow for this step of the project.

To investigate EGR more fully, a laboratory EGR system was prepared that split-off some of the exhaust from the tailpipe at a point downstream of the muffler. The exhaust then passed through a simple two-pass single large tube air-to-water-heat exchanger and then through a flow measuring section thin plate orifice, a manual, gate type, control valve and then to the intake manifold.

The system shown in Figure 11 was designed to permit EGR at a specified flow in percent of carburetor intake air flow rate at 5, 10, 15, and 20 percent. These tests were made with the air injection system inoperative. The heat exchanger was a low pressure drop simple two-pass unit made hurriedly from 4-inch steel exhaust pipe with a total length of 18 ft. The outlet temperature was on the order of 95 to 100°F and represented what might be possible with a good air-to-air heat exchanger on a moderately cool day.

The return of the exhaust into the intake manifold was through two 1/4" pipe openings (1.05 inch ID opening in manifold). It is known that the distribution and mixing, etc., of recycled exhaust with the carbureted fuel-air mixture is tricky and requires substantial effort to perfect. In the very short time available, it was decided to add another 1/4" pipe opening directly across from the one already machined in the experimental manifold used as an access for internal machining for the factory EGR. The system was leak-checked and found satisfactory for a preliminary evaluation

of EGR on the engine by the 23-mode schedule. It was a laboratory system used strictly for basic experimental purposes.

The results, all obtained at standard timing of 4° BTDC with standard carburetor, etc., are plotted in Figure 12 for EGR at various percentages of total engine requirement defined as:

$$\text{Percent EGR} = \frac{\text{EGR (SCFM)} \times 100\%}{\text{Total Flow Requirement (SCFM)}}$$

$$= \frac{\text{EGR (SCFM)} \times 100\%}{\text{Carburetor Air (SCFM)} + \text{EGR (SCFM)}}$$

The results are reduced to the 23-mode values, plotted in Figure 12, using the carbon balance method that has been employed throughout this project to determine exhaust mass rate. Recall that carbon bearing compounds, such as HC, CO, and CO_2 and fuel input are necessary measurements for this computation method. It can be shown, though it is not necessarily obvious, that this method will determine the mass of exhaust products exhausted into the atmosphere even though some of the exhaust is recirculated. The method is valid if the recirculated exhaust is admitted after the carburetor and throttle plate. It should be understood that EGR can reduce the mass of exhaust products emitted to the atmosphere. For example, at wide open throttle and constant speed, the mass flow rate of emissions can be less even though the concentrations of HC and CO are not reduced.

From Figure 12 the laboratory EGR was found to be quite effective on reducing NO_x. At about 10 percent EGR, the benefits of increased EGR are more than offset by the apparent steep increases in emission rates of HC and CO. Though 10 percent EGR was not necessarily optimum, it is probably in this vicinity that best NO_x control results under the 23-mode schedule. Above 10 percent EGR, the engine, at 1200 rpm, would not run when the power level was about 75 percent (15 percent EGR) and 50 percent load (20 percent EGR).

It is interesting to follow the effect of EGR on brake specific fuel consumption and on maximum power output. These results are summarized below. The cycle weighted BSFC results are also plotted on Figure 12. The BSFC and power loss at 10 percent EGR is substantial relative to no

Percent EGR	Overall BSFC 23-Mode Weighted	Power Output, Max bhp, Obs 1200 rpm	2300 rpm
0	0.648	52	108
5	0.681	50	99
10	0.750	47	88
15	0.915	42	78
20	1.075	35	67

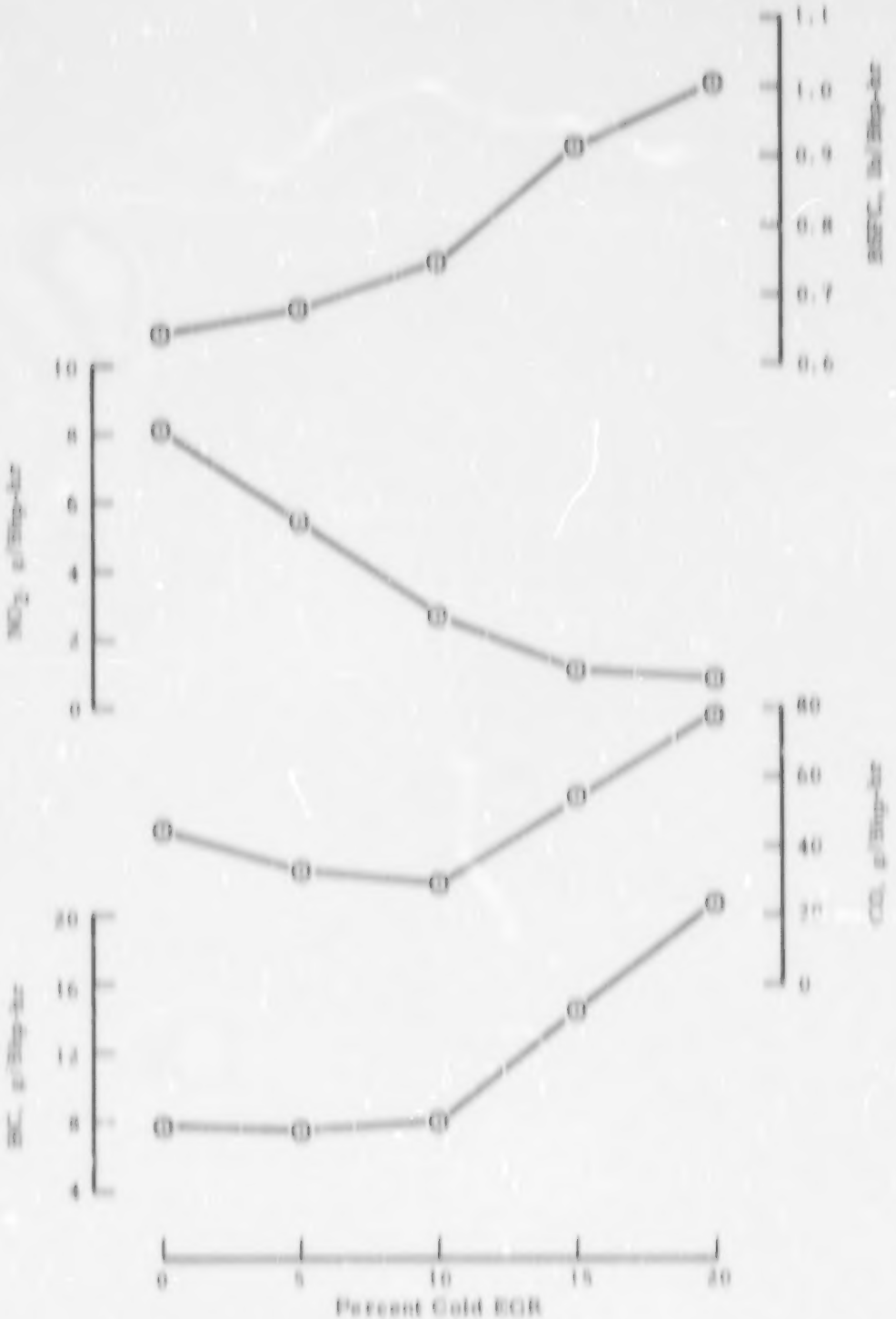


FIGURE 12. EFFECT OF LABORATORY CCLD EGR ON EMISSIONS ENGINE 2-3, 23 MODE TEST

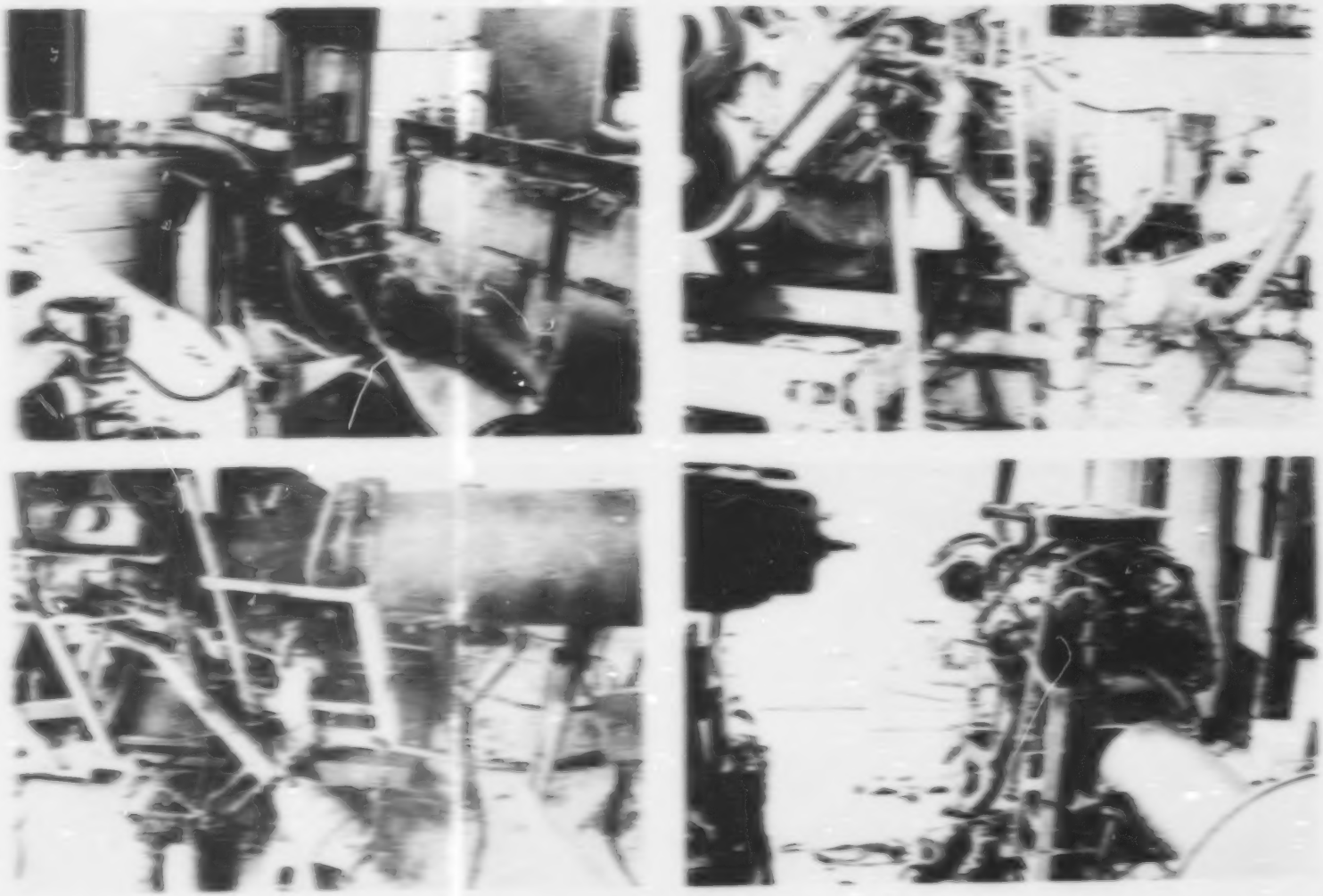


FIGURE 11. OXIDATION CATALYST TEST SET-UP
ENGINE 2-3

EGR. The maximum power could be restored by eliminating EGR at WOT. This will help BSFC only slightly however, since BSFC is a weighted value per the 23-mode test.

The results of this series of tests are included in Appendix I, both in tabular and graphical form. Please refer to this Appendix for additional details. In conclusion, no tests were made to optimize for best performance taking into account fuel economy, brake specific fuel consumption, and driveability aspects such as roughness, misfiring, etc. It does point toward the possible benefits of EGR and illustrates what EGR might do for emissions from this size and make engine on a 23-mode or engine exercise type test schedule.

From the modal results in Appendix I, it is possible to select an EGR schedule that is optimum for NO_x that, in combination with other systems to remove CO and HC, could be driveable. The time limitations of this project have prevented this from being done on an engine. The results may be predicted, however, from data at various timing, air injection, carburetor settings with and without oxidation catalyst. Some combination effects may be seen from factory EGR plus catalysts and air injection at modified spark timing to allow a reasonable prediction.

(g) Step 6 - Effect of an Oxidation Catalyst on Emissions

This series of tests were made with Indolene clear, a well known American Oil Company low lead fuel that is a laboratory standard fuel for operation of devices such as catalytic mufflers. To prepare for these tests, a new fuel pump and fuel handling system up to the carburetor was installed and the carburetor bowl drained. A gallon of Indolene clear was run through the engine before the catalysts were installed. The exhaust system was replaced with new pipe such that the inlet of each of the two catalytic devices were located twenty inches from the exhaust manifold outlet flange. The dual exhausts were then joined together into a single exhaust. The conventional stock muffler was removed.

Samples were obtained from the exhaust at a point five feet downstream for analysis. A common sample of the gases as they entered the devices was obtained at a point one inch before each catalyst and these two samples "Teed" together to obtain a common sample for analysis. Thus, by alternatively sampling the inlet and exit gases, it was possible to determine relative effectiveness of the catalyst.

Inlet and outlet temperatures and pressures were also measured and recorded. The manufacturer required that the exit temperature never exceed 1800°F. This temperature was closely monitored at each condition to make certain the catalyst was not damaged. The manufacturer felt that for the catalyst to be effective, a minimum inlet temperature on the order of 800°F would be needed. There are a number of operating modes in the

23-mode schedule where thir was not possible even with the catalysts close-mounted.

Figure 13 illustrates the installation and sampling arrangement for this step of the project. Additional air for oxidation was provided by the exhaust manifold air injection system normally used for such purposes.

Figure 14 shows the "before" and "after" HC, CO and NO_x for the series of tests made with the oxidation type catalyst. It is difficult to make a direct comparison between the results on Figure 14 and other treatments such as the standard engine with air injection alone, or light duty EGR as were described on Figure 9. This is because fuel and exhaust systems were different, as was the point at which the exhaust was obtained, especially the "before" sample. Incidentally, audible detonation or knock, though intermittent, was experienced on the Indolene Clear at 17 and 25° BTDC when operating at part to WOT throttle position at 1200 and 2300 rpm (above 50 percent power). The knock was not excessive though it was worse at 1200 than at 2300 rpm. An accurate indication of the catalysts effectiveness is, however, portrayed by Figure 14 as to its dramatic reduction of both HC and CO. BSFC, computed on a cycle weighted basis, shows a minimum at 16°BTDC.

Figure 15 is a bar chart representation of the influence of the catalyst on emissions when non-standard carburetor jets and rods (0.075 and 0.028) were employed to richen the mixture. Also, the effect of the catalysts on emissions without air injection is shown. This test, made at standard timing, indicates the need for supplemental air for adequate catalyst operation with this particular engine. In any event, CO reduction was judged poor.

Richening the mixture lowered NO_x, but in doing so, increased CO substantially while having the same effect on HC. It seems that the catalyst is capable of removing a certain amount of CO under the conditions experienced and purposely increasing fuel to air to quench NO formation is not adequately compensated for by the catalyst as tested. Possibly more surface area, i.e., two in series with additional air injection may have helped, though the temperature release can become excessive.

Appendix M contains the tabular and graphed results of the exhaust emissions, etc., for this series of tests. Computer print-outs for the "before" and "after" test series are included. The "after" results, i.e., the emission rates from the engine after passing through the catalyst devices, are plotted against percent power per the 23-mode test.

In summary, it appears that an oxidation catalyst of the type tested has great promise in reducing tailpipe emissions from engine 2-3 on the experimental 23-mode test procedure. Though a sweeping statement regarding the use of catalysts on trucks and their durability cannot be made,

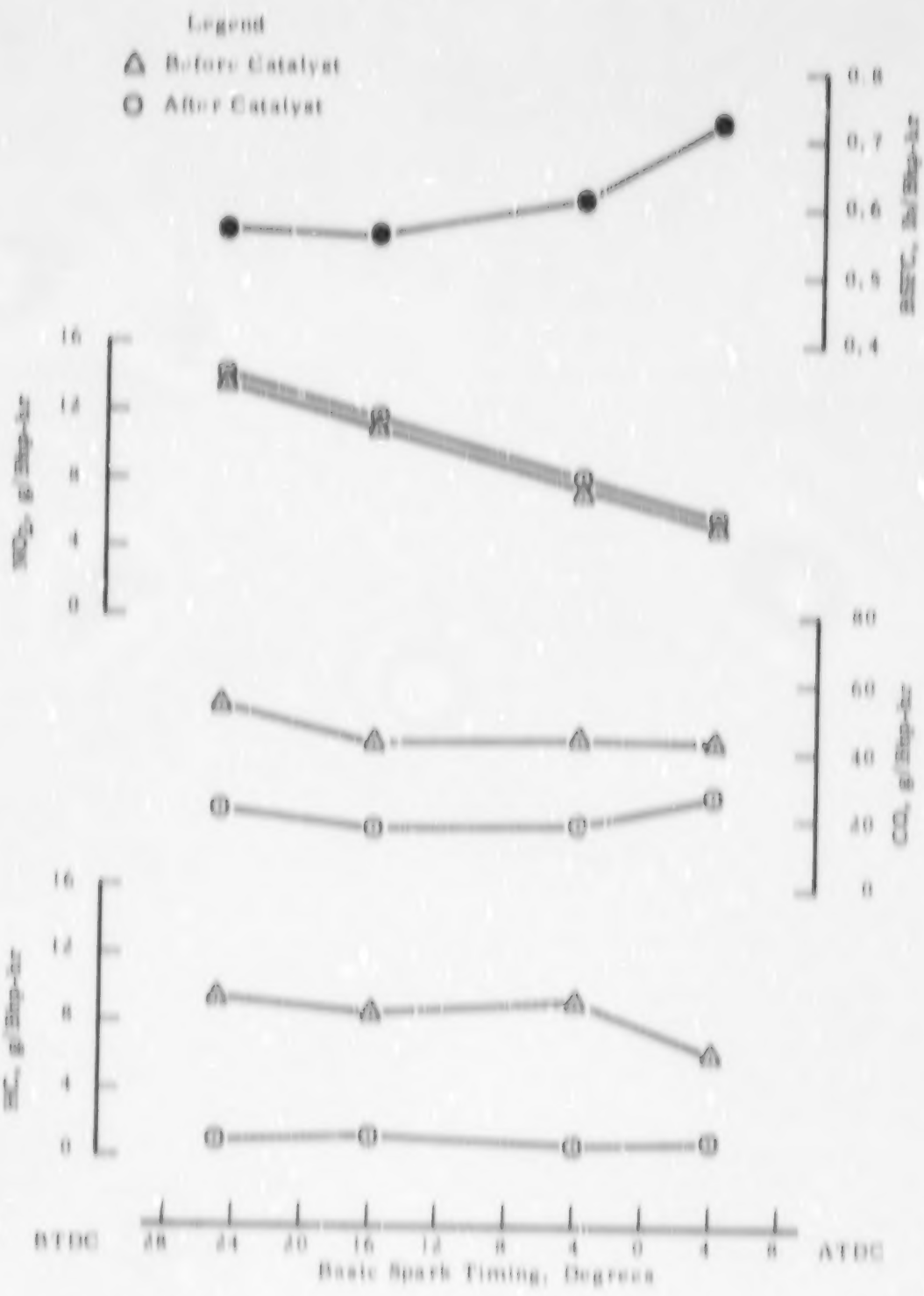


FIGURE 14. EFFECT OF OXIDATION CATALYST ON EMISSIONS ENGINE 2-3, 13 MODE TEST

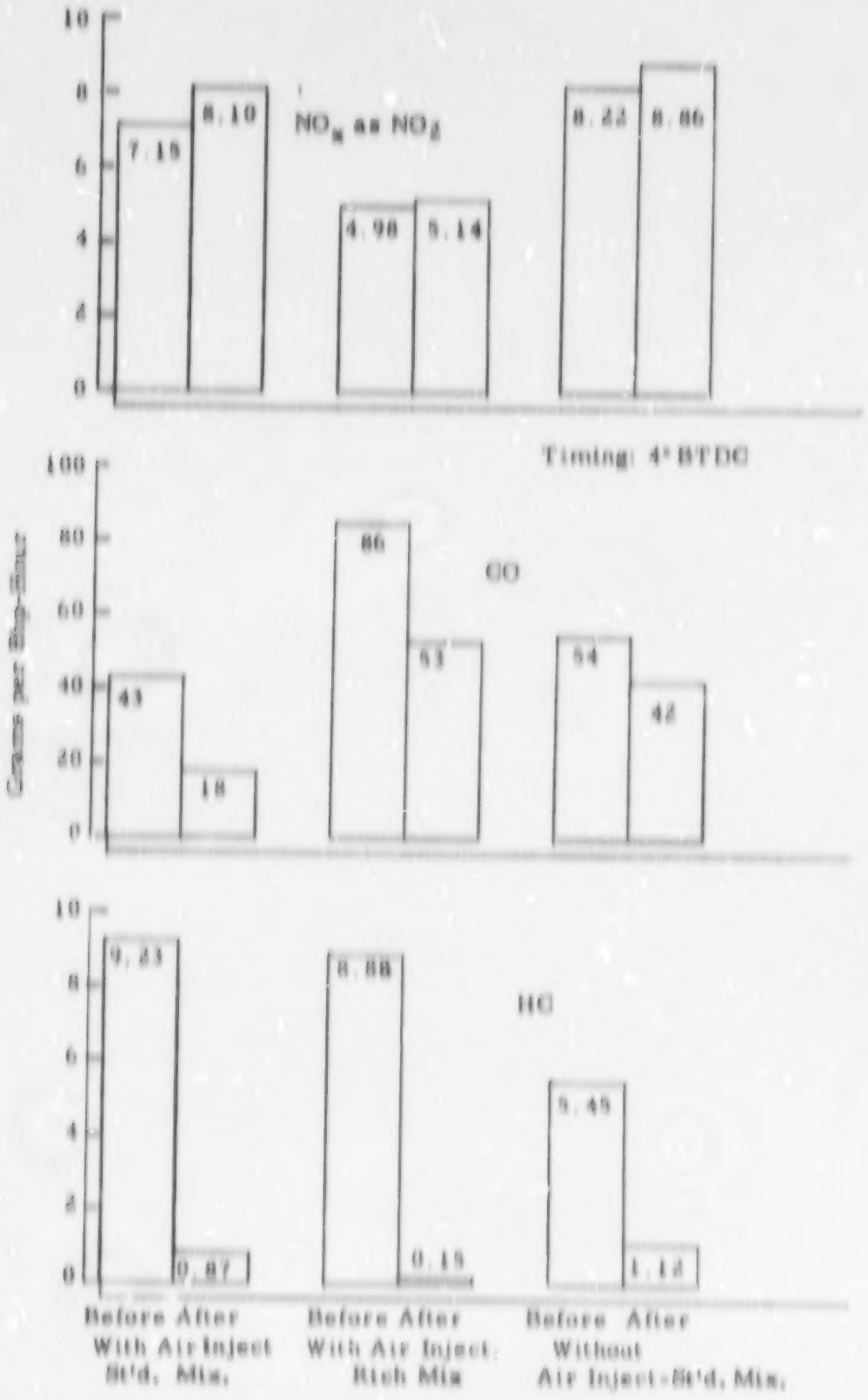


FIGURE 15. EFFECT OF OXIDATION CATALYST ON 1972 STANDARD ENGINE WITHOUT AIR AND WITH FUEL RICH MIXTURE ENGINE 8-3, 23 MODE TEST

the improvements in emission concentrations and mass rates tend to agree with the extensive light-duty experience with this commercially available material. Whether it is sufficiently durable in truck service and whether lead sterile fuel is available are factors that remain to be seen. There were no obvious engine malfunctions or problems due to the catalyst that might affect driveability since no changes are necessarily needed to the carburetor and distributor or the engine to obtain the improvements noted. There are controls that must be applied to prevent the item from being run on fuel containing lead at excessive temperatures (i.e., with excessive CO and HC, etc.), and in isolating the items such as reactor and adjacent piping that experience high temperatures from the vehicle or the environment.

(h) Step 7 - Derating by Carburetor Restriction

This item, of low priority, was considered of interest since the effect of a power reduction on emissions might more than compensate for the power loss that may be associated with some controls. Incidentally, in several steps of this phase, the engine power output was unintentionally derated because of the control device characteristics.

One fairly simple way to intentionally derate the engine was to operate engine 2-3 with only the front two, small, venturis of the four barrel Rochester carburetor. A plate was made that effectively blocked off the rear two venturis, which normally are not in use, and a 23-mode test was run. The engine appeared to run fine at 1200 and at 2300 rpm with little derating of power at 2300 rpm noted. No doubt, that the engine's high speed power was reduced, but at the two speeds used in the 23-mode test schedule, only about 8 percent loss in peak power was found at 2300 rpm. The tests of this item were terminated at this point since time and funds did not permit further testing. Operation on only one barrel was considered, but would require a special mixing section between the carburetor and the intake manifold to improve mixture distribution.

The results of the single run are compared below with a standard engine with unmodified carburetor. Only CO seemed affected to any extent, however, this result has not been verified by sufficient replication.

	grams per bhp-hr 23-mode					
	HC	CO	NO_x	BSFC*	Max. Power, hp **	
Standard Engine						
Carburetor Standard	7.01	56.2	8.6	0.621	@ 1200	53
					2300	114
Standard Engine						
Rear Barrels of Carburetor Blocked	7.97	32.4	9.3	0.609	1200	53
					2300	105

*Weighted per 23-mode test.
**Observed flywheel.

For further details on this single test, please refer to Appendix N.

(i) Step 8 - Combination Tests

The test plan called for combination of the best features of experiments in previous steps and then performing emissions tests. A natural adjunct of this step would be optimization of the control combination(s). The limited time and funds prevented this from being done and only the one best overall combination, with slight variation, was tested. The test series involved 23-mode tests, then nine-mode tests, then additional 23-mode tests with aldehyde measurement (extended tests). Then the engine was returned to original condition as closely as possible and a 23-mode, nine-mode series performed.

The combination tested was standard 4° BTDC spark timing, standard carburator jets, standard, light-duty EGR, oxidation catalyst and manifold air injection. For comparison, the results are shown in Table 12. Samples were obtained before and after the oxidation catalyst. No optimization or calibration was made of the control engine. A 4°ATDC alternative to the standard 4° BTDC was tried. The slight improvements in emissions hardly justified the loss in fuel economy, i.e., higher brake specific fuel consumption.

The second entry on Table 12 summarizes the results of a series of runs made after the engine was returned to its original, standard, 1972 configuration for direct comparison to the tests made on 6-15, 16-72. The standard engine did not change materially during the two months of experimentation. Appendix P contains the run results for the two 23-mode tests made on 8-3-72 with the engine returned to standard configuration.

Using the last, 8-3-72, test made on the standard engine as a basis for reference, the following comparison is offered. Roughly a 70 percent reduction in HC (from 7.31 to 2.13 grams per bhp-hour), a 60 percent reduction in CO (from 51.4 to 16.61 grams per bhp-hour), a 30 percent reduction in NO_2 (from 9.0 to 6.24 grams per bhp-hour), and a 58 percent reduction in aldehydes (from 0.262 to 0.110 grams per bhp-hour) was obtained. This was achieved with only a nominal change in cycle weighted BSFC from 0.622 to 0.668 or a 7.4 percent change (loss) and essentially no change in top end power at 4300 rpm.

More could be done to improve control effectiveness given additional time and funds. A different EGR schedule, tailored to the 23-mode test, would have shown more improvement in NO_x for example or a reduction catalyst may well have made an even greater reduction in NO_x. An advanced technology oxidation catalyst might have done more to reduce CO, HC, and aldehydes as well.

TABLE 14. ENGINE 2-3, 23-MODE EMISSION REDUCTIONS

Configuration	Date	Runs	Grams/bhp-hour, average HC	CO	NO_x	Aldehyde	BSFC	Hp. Obs. @ 2300 rpm
Standard 1972	6-15,16-72	2	7.01	56.20	8.60	0.262	0.621	114
Standard 1972	8-3-72	2	7.31	51.40	9.00	N/A	0.622	109
Controlled*	7-28,8-1,2-72						0.668	
Before Cat.		4	13.08	28.99	6.20	N/A		110
After Cat.			2.13	16.61	6.24	0.110		
Controlled**	7-28-72	1				N/A	0.827	97
Before Cat.			8.33	29.08	4.35			
After Cat.			1.67	18.92	4.23			

*1972 Standard Engine with oxidation catalyst and Light Duty Air Injection and EGR system.
**Same as *, but 4° ATDC Basic Timing.

In conclusion, the extent of control is far from optimum and appears to be a minima. evel that could be achieved using commercially available devices. Though the engine was never installed in a truck and the resulting driveability assessed, it is unlikely that a serious impairment will result since the light duty EGR schedule was adhered to and timing was unchanged. Only negligible changes in power output and brake specific fuel consumption resulted based on the 23-mode test.

For additional details, modal and individual 23-mode run results, please refer to Appendix O. The tabular data in Appendix O for the four runs made with the best combination on 7-28, 8-1, 2- 1972 show satisfactory test repeatability. The graphed results for the best combination, after catalyst, are shown in Figures 0-1 through 0-3 for HC, CO and NO_x, and are included for further consideration if desired.

Tests were also made using the nine-mode FTP with the results expressed in concentration and grams per bhp-hour. These results are summarized in Tables 13 and 14. The first two entries in both tables, for Standard 1972, show good agreement even though over two months had elapsed between tests of this configuration.

Comparing the Table 13 concentration results with the controlled engine to those with the most recent test series in standard configuration, the emission controlled engine must be termed an improvement with regard to CO and NO, but a penalty regarding HC. This same conclusion may be

TABLE 13. ENGINE Z-3 NINE-MODE 1972 FTP EMISSION REDUCTIONS
(Concentration Basis)

Configuration	Date	Runs	Concentrations, Average HC ppm Hex.	CO, %	NO, ppm Corr.
Standard 1972	5-12-72	3	116	0.66	1601
Standard 1972	8-4-72	3	117	0.57	1660
Controlled*	8-2-72	3	129	0.09	641
Current Federal Limit			275	1.5	None
Proposed Federal Limit			160	0.8	2000

*1972 Standard Engine with oxidation catalyst, Light Duty Air Injection, and EGR System.

TABLE 14. ENGINE Z-3 NINE-MODE 1974 FTP EMISSION REDUCTIONS
(Mass Basis)

Configuration	Date	Runs	Grams/Bhp-Hour, Average CO	HC	NO_x	HC + NO_x
Standard 1972	5-12-72	3	31.4	3.36	11.20	14.56
Standard 1972	8-4-72	3	22.1	2.87	9.74	12.61
Controlled*	8-2-72	3	4.7	2.86	6.26	9.12
1973 California Limit			40			16
1975 California Limit			25			9

*1972 Standard Engine with oxidation catalyst, Light Duty Air Injection and EGR System.

reached from the data in Table 14. Although the nine-mode CO and NO results seem fairly consistent with the 23-mode, HC definitely was not. Incidentally, the nine-mode overstates the reduction made in CO relative to the 23 mode test while the nine-mode seems to understate the HC improvement relative to the 23 mode. Had the nine-mode FTP been used to evaluate the control technology assessment instead of the 23-mode test, it is unlikely that the same optimization of the final emissions control system would have been used.

It appears that the catalyst and air pump did little if anything to reduce HC even though it is known by the 23-mode test mode-by-mode results that it was doing a job.

To try and understand more about what causes these apparent inconsistencies, a mode-by-mode analysis of nine-mode FTP results in standard and control equipped configuration was made. Table 15 lists the dilution factors and weighting factors for the average standard and the average control equipped run. Also listed are the average CO_2 raw concentrations which have the major influence on the dilution factor. The air pump dilutes the exhaust sufficiently to cause the modal difference shown, and when multiplied by the appropriate FTP weighting factor and summed, the air pump can be seen to change the overall dilution factor from near unity (1.1) as normal, to 1.7.

The dilution factor is not, however, the only reason since it affects CO and NO also. It then reverts to the ability of the control system to show the large reductions throughout the nine-mode test, especially those with a large dilution and weighting factor. Data to substantiate this are also listed on Table 15. Note the raw, adjusted (for dilution) and weighted HC values for standard and controlled. For discussion, consider the weighted HC for each engine configuration.

Modes 1, 3, 7, and 8 (Idle, 10-inch, 3-inch, and the last 16-inch Hg intake manifold vacuum) were lower with the controlled engine. Modes 2, 4, and 6, all 16-inch, modes 5 and 9, the 19-inch and closed throttle, were substantially higher in some cases with the controlled engine. The modes in which the controlled engine was better than standard amount to 66.5 percent of the cycle weight. Even so, the rather poor performance of the controlled engine, i.e., HC worse than standard due to EGR, etc., caused the HC to remain about the same overall.

A history effect may also be noted by looking at the repeated 16-inch condition, modes 2, 4, 6, and 8. Apparently the catalyst and air injection system, which depend heavily on available heat energy in the exhaust stream, were adversely affected by the prior conditions. Only after the 3-inch, near wide open throttle condition was the catalyst effective on hydrocarbons. The 19-inch, mode 5, was quite interesting since apparently the EGR spoiled normal combustion with insufficient heat energy available from the mode or previous mode to effect any clean-up. When using the light duty EGR system, employed in the 23 mode runs, it would be necessary to develop a different rate controller component to preclude operation under those conditions of the nine-mode schedule where EGR had an adverse effect. For further analysis of the data along these and other lines, please refer to Appendix O and P. Appendix O contains nine-mode concentration and mass results with the "best combination" while concentration and mass results by the FTP are included in Appendix P.

TABLE IV. ANALYSIS OF 1994 MODE FTP HC RESULTS
ENGINE 2-3

Mode	Intake Vac. in Hg.	Wt. Fact.	Standard 1972 Raw CO_2, %	Dil. Fact.	HC, ppm x Dry, Raw	Adjusted	Weighted	Controlled Raw CO_2, %	Dil. Fact.	HC, ppm x Dry, Raw	Adjusted	Weighted
1	28e	0.034	13.32	1.852	297	304	7.74	9.89	1.565	23	36	1.30
2	16	0.049	13.35	1.673	41	47	7.78	6.79	1.635	148	385	27.15
3	19	0.257	13.91	1.963	49	52	13.36	10.67	1.358	13	18	4.63
4	16	0.049	13.4+	1.864	44	47	4.1+	9.88	1.597	56	69	7.92
5	19	0.047	13.42	1.863	30	32	1.58	7.82	1.864	647	1299	56.62
6	16	0.049	13.46	1.867	42	45	4.81	9.85	1.583	72	114	10.15
7	3	0.263	13.98	0.996	74	74	22.07	13.15	1.068	12	13	3.68
8	16	0.049	13.54	1.856	35	37	3.29	9.25	1.640	14	23	2.05
9	Closed Throttle	0.121	4.14	1.354	1955	2628	75.82	4.74	2.673	328	919	19.38
						TOTAL	116.95					133.86

In summary of the nine-mode FTP experiments, the emission results appear quite cycle dependent. The findings here do not necessarily conflict with earlier reported data which showed that the 1973 standard version to give higher emission results than the 1972 standard version by the 23-mode test, yet represented an improvement by the nine-mode FTP. It means that it depends on how one goes about reducing emissions. On one procedure it may help and on another, it may not.

(j) Step 9 - Other Methods

Time and financial limitations constrained this research to the previous items listed. However, several other promising control approaches applicable to the gasoline truck above 6,000 lbs. were seriously considered. Turbocharging was considered seriously enough to request engineering and performance data from the manufacturer, who provided turbochargers appropriate for engines 2-3 and 1-3. Time and funds precluded their inclusion in the test program.

Electronic fuel injection was also investigated with representatives of a leading component company. Such a system, though under active development for use on engines similar to numbers 2-3 and 1-3, was not available for our test. There are programs in progress to bring electronic fuel injection to a reality in the future and this method and its potential for control should not be overlooked. Electronic fuel injection with closed loop control, seems to be the ultimate and its potential emissions benefit could be substantial.

The third major item, and one that was nearly included, was a reduction catalyst for NO_x control. This item was disclosed at the EPA suspension hearings in April of 1973 with dramatic performance on NO_x claimed on the light-duty test. Used in combination with an oxidation catalyst, the strict 1976 light-duty standards were claimed to be met. Repeated attempts to obtain samples for evaluation resulted in an impasse regarding the rights-in-data clause of the manufacturer's Non-Disclosure Agreement. This point could not be resolved in the time remaining under the project and accordingly the item was not evaluated. Had there been at least a month of test time available for engine-catalyst optimization, this issue could have been resolved. The short time frame for testing under this project made this impossible. These three major items should definitely be included in any future control technology assessment project. They all have potential for heavy-duty trucks.

3. Engine 1-3 Control Technology Results

Tests were conducted on this engine following the preliminary plan of test shown on Table 16. This schedule was revised some from that originally provided the Project Officer by letter dated July 18, 1973 in that

TABLE 16. PLAN OF TEST, ENGINE 1-3

Step	Description
1.	Very basic timing i.e. say 10° advanced,standard and 10° retarded timing.
2.	Install larger and smaller carburetor jets to modify engine air-fuel ratio at standard timing.
3.	Run laboratory EGR system at standard timing at say 5, 10, and 15 percent total intake air flow as EGR.
4.	Operate exhaust manifold air injection system at standard, advanced, and retarded basic spark timing with standard carburetor.
5.	Install oxidation type catalytic reactor, clean fuel system, and run with air pump at standard timing, advanced and/or retarded. Operate on clear fuel (unleaded), run longer modes and sample exhaust before and after catalysts.
6.	Combine best EGR or catalyst - ignition timing found in Steps 2, 3, 4, and 5.

the reduction catalyst alternative was deleted with its non-availability. Discussions with the engine manufacturer were successful in obtaining carburetor jets larger and smaller in size than standard. Also furnished by the engine manufacturer were cylinder heads and associated air pump valve and tubing for exhaust manifold oxidation experiments. The work plan was a simplified, abbreviated, series that was similar in scope to that used for engine 4-3.

Before starting the test program, the engine heads were removed and replaced with the factory-furnished standard light-duty heads normally used to inject air into the exhaust stream as it leaves the combustion chamber. The heads were all new with new valves, springs, etc. The air pump delivery hoses and tubing for connection of the pump to the injection tubes were installed and connected. The vacuum-operated distribution valve, which is intended to prevent possible exhaust backfiring during closed throttle, was also installed and connected as specified by the manufacturer.

The laboratory exhaust gas recirculation system was identical to that used with engine 4-3. One major difference was the way in which the recirculated exhaust was introduced into the engine. As pointed out with engine 4-3, this is very important in order to maintain even mixture distribution, etc. In the short period of time available, it was decided to use a separate plastic distribution block under the carburetor much as the positive crankcase ventilation system uses. To simplify the design, it was decided to use the same type of plastic block as is used for the PCV and locate both between the carburetor and the intake manifold. To facilitate connection of the EGR and PCV hoses, a 1/4 inch thick aluminum block was inserted between the two plastic blocks. The plastic block has a nicely formed passageway communicating from the common inlet to each of the two openings (barrels) and was well suited for even distribution of the EGR to each throat of the intake system.

It was during the reassembly of the carburetor on the taller stack of items that one ear of the bottom flange of the carburetor broke off. It was felt that a replacement carburetor should be obtained from from the manufacturer and after some conversation with the manufacturer's representative, it was decided to use a 1973 carburetor, not a 1974 unit. They are identical except in jet size. The change in jets was so slight, according to the manufacturer, that it would be within the normal carburetor production tolerance.

The pair of oxidation catalysts were installed as with engine 4-3. The inlets were positioned 40 inches from each engine bank's exhaust manifold flange. The dual exhausts were then connected into a single exhaust pipe and stock muffler. The sample probes were positioned as with engine 4-3 with provision for sampling before and after the catalysts. When the catalytic reactors were not to be tested, they were removed and short, straight pipes inserted in their place.

All operation was with leaded emissions test gasoline except when the catalytic reactors were installed necessitating the use of low lead, Indolene clear, fuel. Figures 16 and 17 show various views of the engine prepared for test. Some of the test items and instruments are also shown.

(a) Step I - Effect of Basic Spark Timing on Emissions

The following, Table 17, lists the 23-mode results at various basic spark timings:

TABLE 17. EFFECT OF BASIC SPARK TIMING ON EMISSIONS
23-MODE TEST, ENGINE 1-5

			Grams per cylinder				Max. Bhp.	
Date	Run	Timing	HC	CO	NO_2 Obs.	Weighted BSFC	1200 rpm	2300 rpm
8-17-72	2	30°BTDC	15.7	64.1	17.9	0.669	56	113
8-17-72	1	15°BTDC	8.7	78.7	13.6	0.679	57	115
8-16-72	2	6° BTDC	9.4	71.3	8.7	0.720	53	110
8-16-72	1	6° BTDC	8.9	72.8	8.7	0.717	53	110
		Average	9.3	72.1	8.7	0.719	53	110
8-18-72	1	TDC*	8.9	110.1	5.8	0.855	46	99
8-17-72	4	5°ATDC*	9.8	187.8	4.3	1.061	42	87
8-17-72	3	10°ATDC*	9.5	187.7	4.6	1.143	35	79

* Engine operational difficulties encountered

The two runs made on 8-16-72 at 6° BTDC represents the standard engine as far as the control technology laboratory studies are concerned. The first tendency is to compare the average with earlier tests on engine 1-5 that were presented under the baseline portion of the results. Such a comparison should be avoided since the heads and carburetor were new and different from those used as baseline. Thus the lower HC and NO_2 and higher CO reported from the modified engine 1-5 than baseline has no basis for comparison.

The data listed in Table 17 are plotted in Figure 18 and illustrate the trade-off between NO_2 and CO with timing. As timing is adjusted later and later, NO_2 decreased almost linearly. CO seemed to take-off upward after operation at the factory standard of 6° BTDC. The question from these curves is, which is most important, CO or NO_2? In one case, a change in timing of 11° from 6° BTDC to 5° ATDC brought NO_2 down to half while the same timing change almost doubled CO by the 23-mode test.

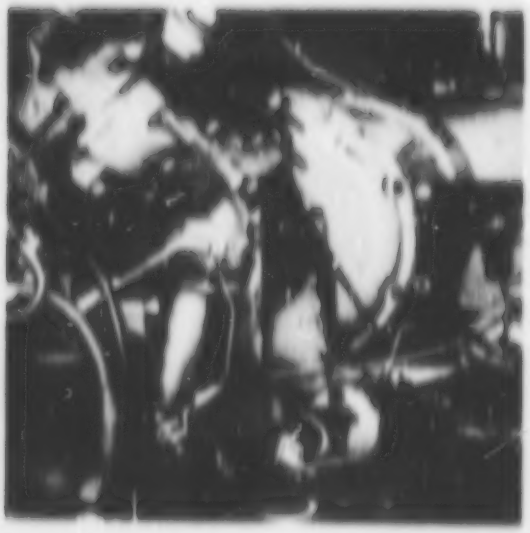
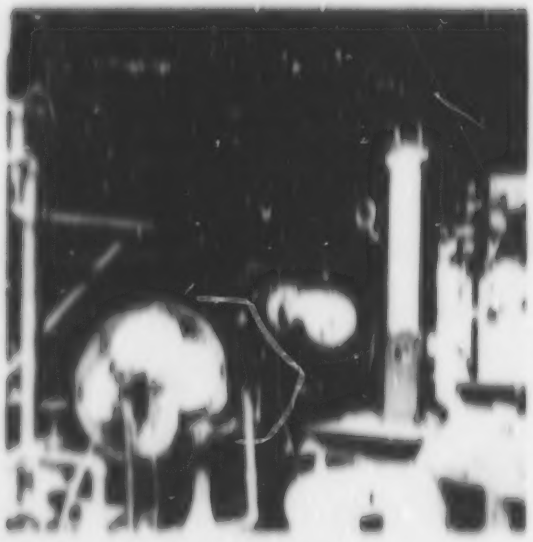


FIGURE 16. VARIOUS VIEWS OF OXIDATION CATALYST AND AIR INJECTION SYSTEM
Engine 1-3



"Cold" EGR

"Hot" EGR

FIGURE 17. LABORATORY SET-UP FOR EGR
Engine 1-3

HC seemed to be little affected by timing. Operational difficulties were encountered at one or more modes at TDC, 5 and 10° ATDC resulting in less than complete 73 mode data. Looking back at Table 17, BSFC was degraded as was top end power at 2300 and 1200 rpm. Cycle weighted BSFC is plotted on Figure 18 for graphical representation. The question from this is: Can the excessive CO be reduced by an oxidation catalyst? Some experiments along these lines will be discussed later.

For more details in terms of computer print-outs and graphs of the results, please refer to Appendix Q. It may be noted from the computer print-outs that several modes were not operable at retarded spark timing. The engine refused to operate at 75 and 82 percent load at 1200 rpm with TDC timing. When the timing was retarded still further from standard, to 5° ATDC and 10° ATDC, the engine would not run at 75, 82 and 92 percent power, 1200 rpm and 75 percent power at 2300 rpm.

(b) Step 2 - Effect of Air-Fuel Ratio on Emissions.

To investigate this effect, the main fuel jets were replaced with smaller and larger items and thereby change the air-fuel ratio. As with engine 2-3, the emissions and BSFC behavior of engine 1-3 was plotted against 23-mode cycle weighted air-fuel ratio. The carburetor main jet size in inches is also indicated. The standard size, 0.056 inch, is shown with two richer jets, 0.060 and 0.065 inch, and one leaner jet, 0.051 inch, on Figure 19. A fairly good plot results from this method of presentation. Attempt to operate with larger and smaller jets than those shown were made with unsatisfactory engine operation resulting.

Figure 19 illustrates that the standard engine could be made to produce less NO but again at the expense of a dramatic increase in CO and a small increase in HC. This approach may have some merit in reducing NO_x, if rich enough jets are used. However, something like an oxidation catalyst will have to destroy CO and HC. The remaining point is whether this approach, which increases weighted BSFC from the reference 0.719 to 0.789 for the 0.060 inch jets, as shown in Figure 19, is worth it. Maximum power at 2300 and 1200 rpm seemed little affected by the 0.060 inch jets. An opportunity to compare a larger jet with a catalytic reactor will be given later in this section. For further details and modal data, both on a tabular and a graphical basis, please refer to Appendix R. The engine would not run in mode 6 with 0.051 jets, and in modes 13 and 14 with 0.065 jets.

(c) Step 3 - Effect of Laboratory EGR on Emissions

This step of the project involved using the laboratory system previously described to recirculate a part of the engine's exhaust back into the intake system below the carburetor throttle plate. The system was normally controlled to recirculate exhaust at a fixed percentage of the engine

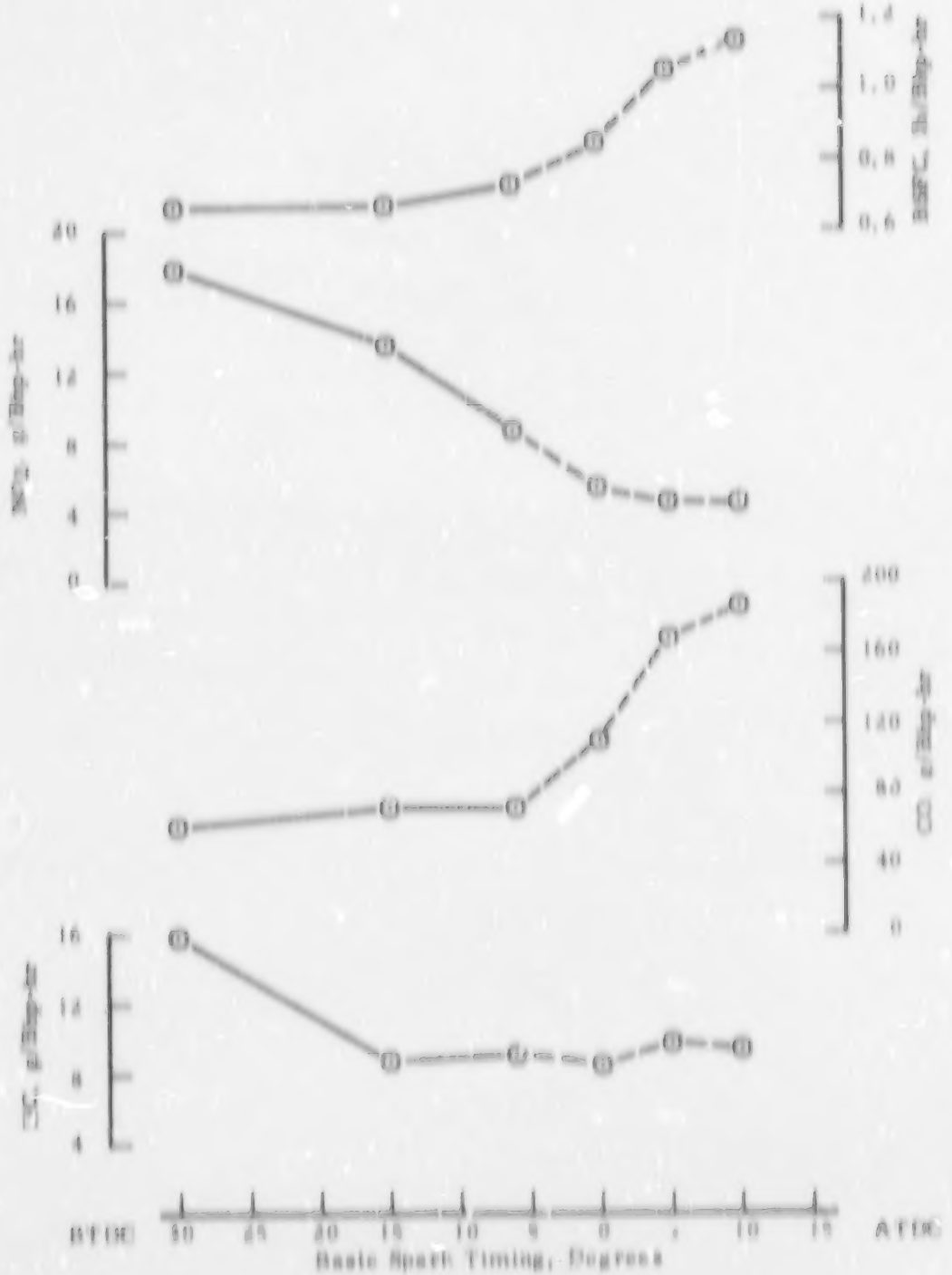


FIGURE 16. EFFECT OF BASIC SPARK TIMING ON EMISSIONS ENGINE I-3, 23 MODE TEST

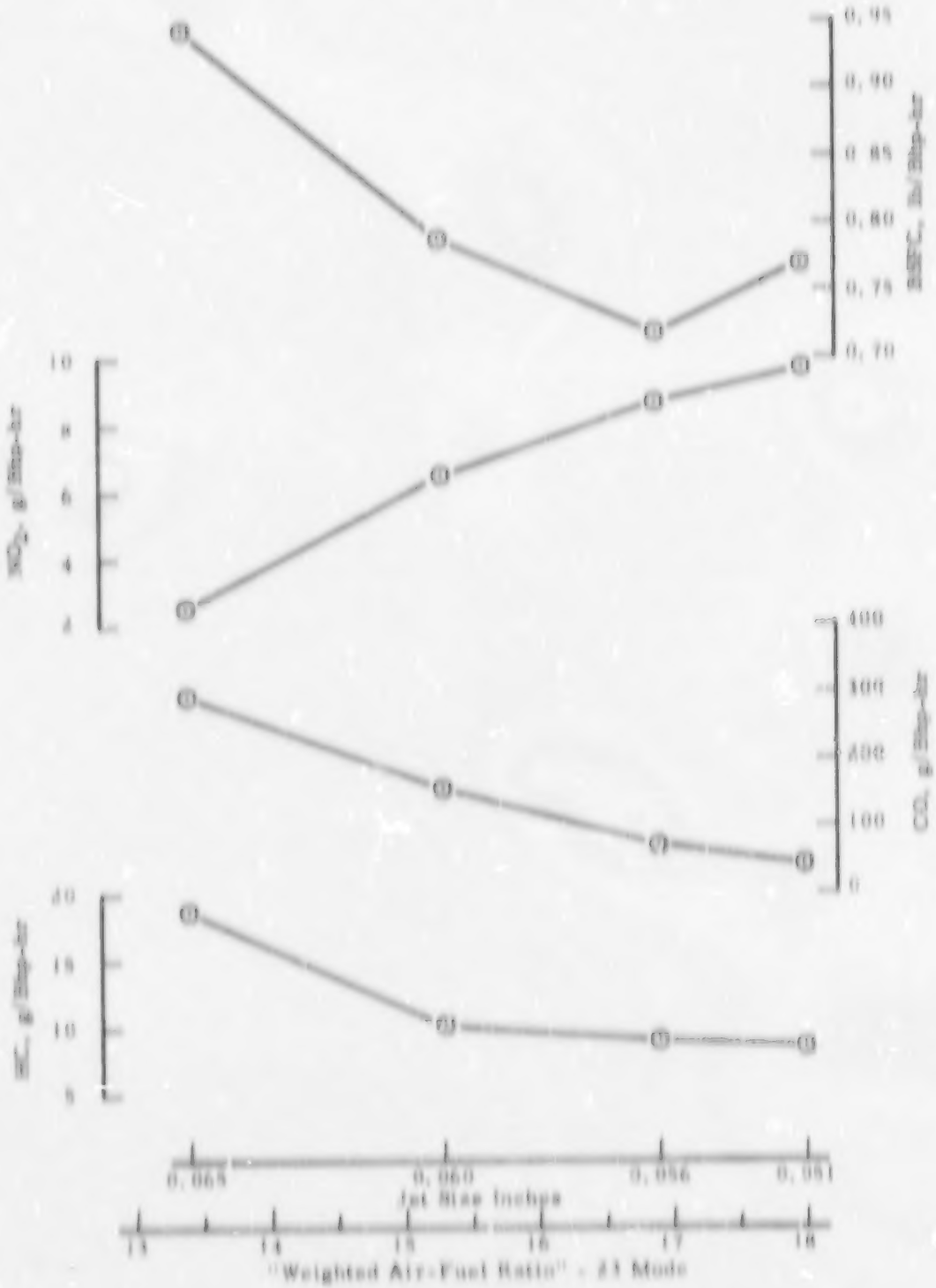


FIGURE 19. EFFECT OF AIR-FUEL RATIO ON EMISSIONS ENGINE 1-3, 13 MODE TEST

inlet flow. The temperature of the recirculated exhaust was generally 100 to 110°F. A strict 13-mode schedule was performed in that the maximum power was first determined using a given fixed EGR rate. Then, the various power points were calculated from the maximum per the usual test procedure.

During the running of the 13-mode test, the dynamometer operator was instructed to maintain certain power output and speed and vary throttle setting to do so. The test engineer would adjust EGR rate to obtain the desired fixed percentage EGR by measuring both the carburetor inlet air and exhaust recycle at the same time and performing necessary calculations. It generally required about five minutes to establish the condition properly before exhaust emission measurements could be made.

Figure 20 depicts the HC, CO, and NO_x emission and cycle weighted BSFC results obtained at 5, 10, and 15 percent EGR. From engine 2-3, it was found that 10 percent EGR was about optimum for NO reduction, yet without seriously jeopardizing engine performance. Accordingly, the EGR rates were selected to bracket 10 percent. Recall that a constant rate of EGR was employed with the exception of closed throttle and idle modes where NO is negligible. Certainly, a constant EGR rate is not optimum for top-end performance or NO_x reduction for that matter. The three constant levels depicted along with zero EGR for reference makes a somewhat complete laboratory study of cooled EGR. The engine was standard otherwise with standard size jets and spark timing.

Cooled EGR has a substantial effect on NO_x formation and results in significant NO_x reductions. Recall that EGR can reduce exhaust volume so that when multiplied by reduced emission concentrations, the result can be substantially lower NO_x. This assumes little or no maximum power output is lost. For additional details, data and graphs covering this series of experiments, please refer to Appendix B. There are many ways the modal data given in Appendix B may be used. One way is to try and derive the best schedule of EGR, tailored to produce minimum NO_x without loss in maximum power, with acceptable increases in CO and HC, assuming an oxidation catalyst, and without seriously impairing fuel economy. It is difficult to obtain a large decrease in NO_x by EGR without increase in fuel consumption. The steady increase in weighted BSFC, Figure 20, points up the fuel and inherent operating cost penalty associated with EGR. As a fairly rapid approximation, the EGR schedules shown in Table 18 were selected for test later in the project.

These schedules will be discussed more in a later section where both cooled EGR and hot EGR will be run at 6° and TDC timing. Hot, or unintentionally cooled EGR seems to be the currently accepted method for light-duty vehicles. The use of hot EGR will undoubtedly lower the charge density and thereby degrade top-end performance. The engine will necessarily run as if it is operating on a very hot day. The water of combustion in the recirculated

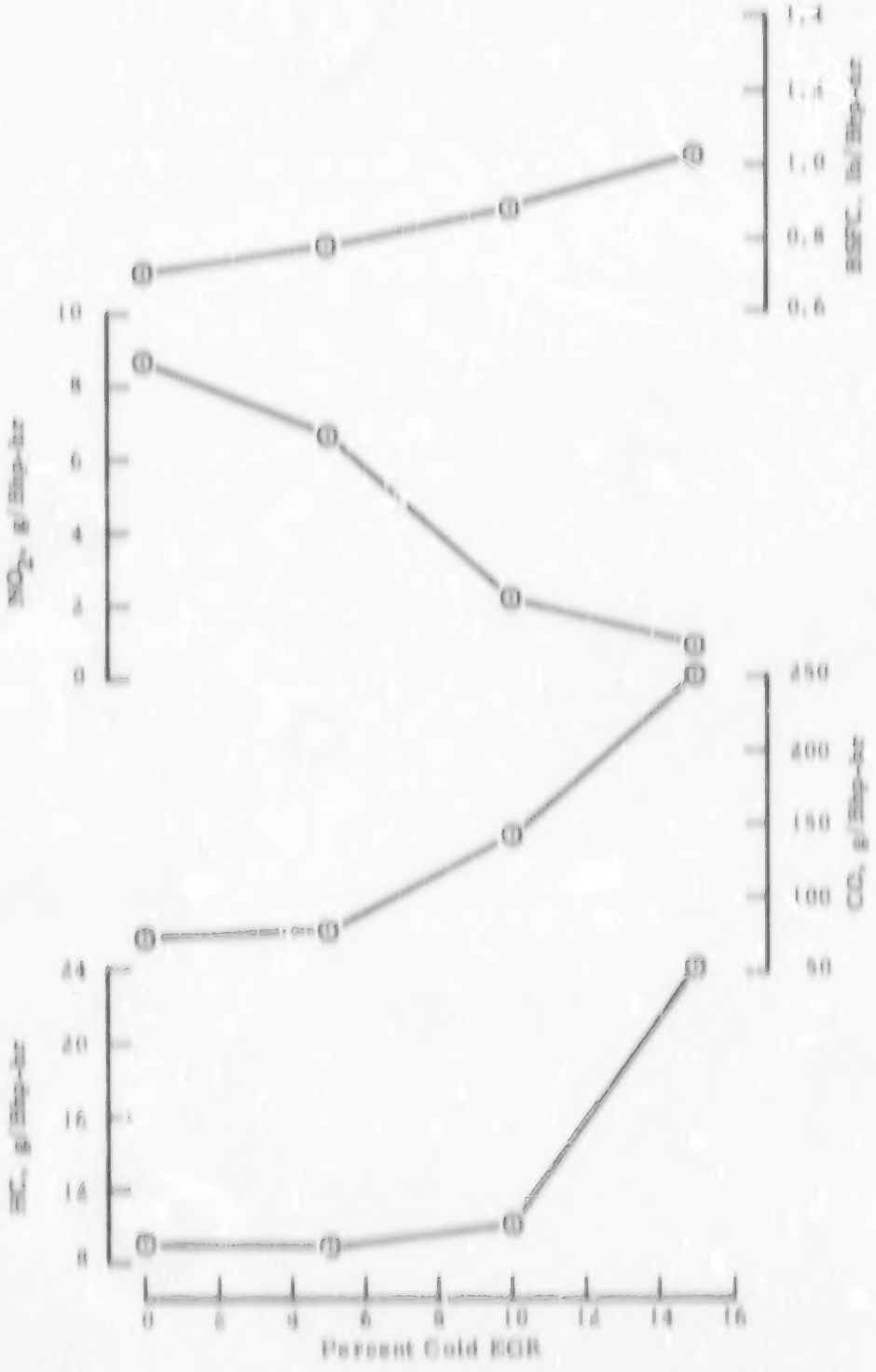


FIGURE 40. EFFECT OF LABORATORY COLD EGR ON EMISSIONS ENGINE 1-3, 13 MODE TEST

exhaust will remain in the recycle and this should help. The EGR will be monitored and adjusted to give a mass percent EGR.

TABLE 18. TAILORED EGR SCHEDULES FOR ENGINE 1-1

Mode	Speed	Percent Load	Percent "Hot" EGR Sch. A	Sch. B	Weight Factor
1	600	0	0	0	0.070
2	1200	2	10	10	0.060
3	1900	8	10	10	0.060
4	1900	18	10	10	0.050
5	1900	29	10	10	0.030
6	1900	50	10	10	0.060
7	1900	75	10	10	0.000
8	1900	82	10	10	0.040
9	1900	92	0	0	0.000
10	1900	100	0	0	0.000
11	600	0	0	0	0.070
12	1200	0(CT)	0	0	0.120
13	2300	100	5	5	0.025
14	2300	92	10	5	0.055
15	2300	85	10	5	0.035
16	2300	75	10	5	0.060
17	2300	50	10	10	0.060
18	2300	25	10	10	0.000
19	2300	18	10	10	0.065
20	2300	8	10	10	0.000
21	2300	2	10	10	0.000
22	600	0	0	0	0.080
23	2300	0(CT)	0	0	0.060

(d) Step 4 - Effect of Factory Air Injection on Emissions

Through the courtesy of the manufacturer, a light-duty air injection system was obtained and utilized in this study. Although air injection by itself had only a slight effect on engine 2-1, it was uncertain what it would do on engine 1-1. In any event, supplemental air or oxygen in the exhaust stream was necessary for oxidation catalyst operation. The light-duty exhaust manifold air injection system is shown in the drawing in Figure 21. It was also shown as installed on the engine in Figure 16 photographs.

The test series involved operation with the complete light-duty system at several basic spark timings namely, TDC, standard (6° BTDC) and 15° BTDC. From Step 1, effect of timing on emission rates, it was shown that this was the range of interest as far as engine operability and emissions

performance was concerned. Table 19 lists the 23-mode results when operating with and without the air injection system operative.

TABLE 19. COMPARISON OF EMISSIONS WITH AND WITHOUT LIGHT-DUTY AIR INJECTION SYSTEM
Engine 1-3, 23-Mode Test

Basic Timing	Configuration	Grams per bhp-hr. HC	CO	NO_x	Weighted BSFC
18° BTDC	with air	10.4	48	10.6	0.667
	without air	8.7	72	13.6	0.679
6° BTDC	with air	9.8	60	8.3	0.712
	without air	9.3	72	8.7	0.719
TDC	with air	9.9	64	6.5	0.768
	without air	8.6	110	5.8	0.858

No really gross or consistent improvement on HC and CO may be found by such a comparison when operating with the air system. In all, air injection as a control item on this engine, subjected to the 23-mode test, lacks justification from an emissions reduction standpoint. It will be necessary, however, to utilize an air pump or something similar to provide supplementary oxygen for the oxidation catalyst. For further details, modal results both tabular and graphical, please refer to Appendix T to this report.

(c) Step 5 - Effect of Oxidation Catalyst on Emissions

Before beginning the experiments with the two precious metal catalytic reactors, the manufacturer of the engine and the catalyst were contacted to make certain the light duty air injection system would deliver the proper amount of air for optimum catalyst performance. In discussions with a representative of the engine manufacturer, it was learned that the vacuum-operated valve, item 2 in View A of Figure 21, could be replaced with a simple "tee" fitting. The vacuum-operated valve acts somewhat as a wastegate so that under some engine vacuum conditions, more or less of the air is wasted and not injected.

There are a number of reasons for this valve in the light-duty system and there may be justification for its use in heavy duty. But, it was decided to eliminate the valve with the concurrence of the manufacturer. Trial runs revealed operation to be satisfactory with no backfiring during the closed throttle conditions, etc. Sufficient O_2 in the exhaust was achieved

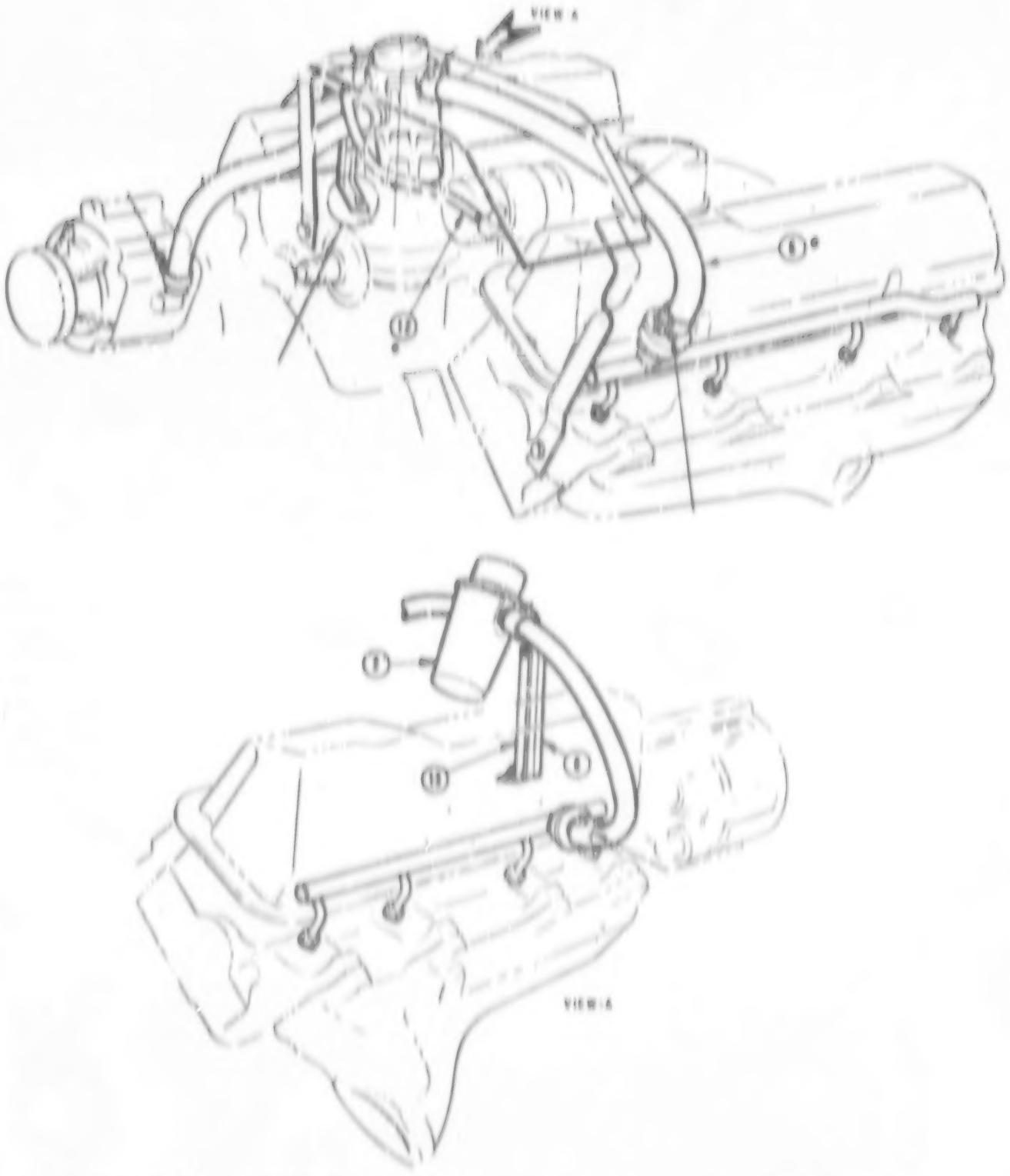


FIGURE 41. LIGHT DUTY EXHAUST MANIFOLD AIR INJECTION SYSTEM

to promote satisfactory catalysts. Please refer to Figure 16 which shows a one-half inch pipe tee used in place of the vacuum valve. The air from the pump is accordingly simply distributed to each bank of the engine.

Figure 22 is a graph of the exhaust emissions measured before and after the catalyst. As with engine 2-3, the catalysts have little effect on NO_x, as expected, an important effect on CO, and a substantial effect on HC. The catalyst must be judged an important item of emissions control and performs a very vital role in lowering CO and HC while not affecting NO_x. It did not seem to matter where the timing was set, although the TDC CO point does not agree in trend with earlier curve of CO versus timing namely, Figure 18. Exactly why CO behavior is erratic at TDC is unknown, but it is apparently not a good engine operating point as mentioned earlier.

The run results made with catalyst treatment are listed on Table 20 and are those plotted on Figure 22. Of interest was the duplicate runs made at 6° BTDC (standard timing) with the light duty air injection system including vacuum-operated distribution valve listed on Table 20. Higher CO and HC by the 23-mode test, were found when the vacuum valve was used. The data points on Figure 22 were obtained with the simple pipe Tee substituted for the waste gate. Weighted BSFC, plotted on Figure 22, shows the familiar increase with retarded timing.

The run results seem to indicate that better emissions control can be achieved with catalyst when the full delivery of the air pump is utilized. It may be thought that the effect is one of more exhaust dilution. But, this is not the case when the calculations are based on the carbon balance method as are the 23-mode and Federal nine-mode mass methods.

From Figure 22, it can be seen that most any timing within the TDC to 15° BTDC range may be selected for about equivalent emission improvement. This is the important conclusion to be drawn from the fairly brief series of tests. The "before" and "after" catalyst data are published in tabular form, as computer print-outs, in Appendix U. The "after" modal grams per hour data are graphed against power level and included in Appendix U for further study.

(f) Step 6 - Effect of Various Combinations on Emissions

A few combinations were experimented with to determine how well various control approaches might work overall. Because of interactions, it is not possible to simply add the benefits of control devices. One combination tried under this step, shown in summary on Table 21, was to look quickly at richer jets, 0.063 inch, the modified light-duty air injection with oxidation catalysts but no EGR. Two basic timing settings of 6° BTDC (standard) and an advanced, 15° BTDC were tried. Although the bigger jets at standard timing with the catalyst gives some reduction in NO_x, the CO is unacceptably

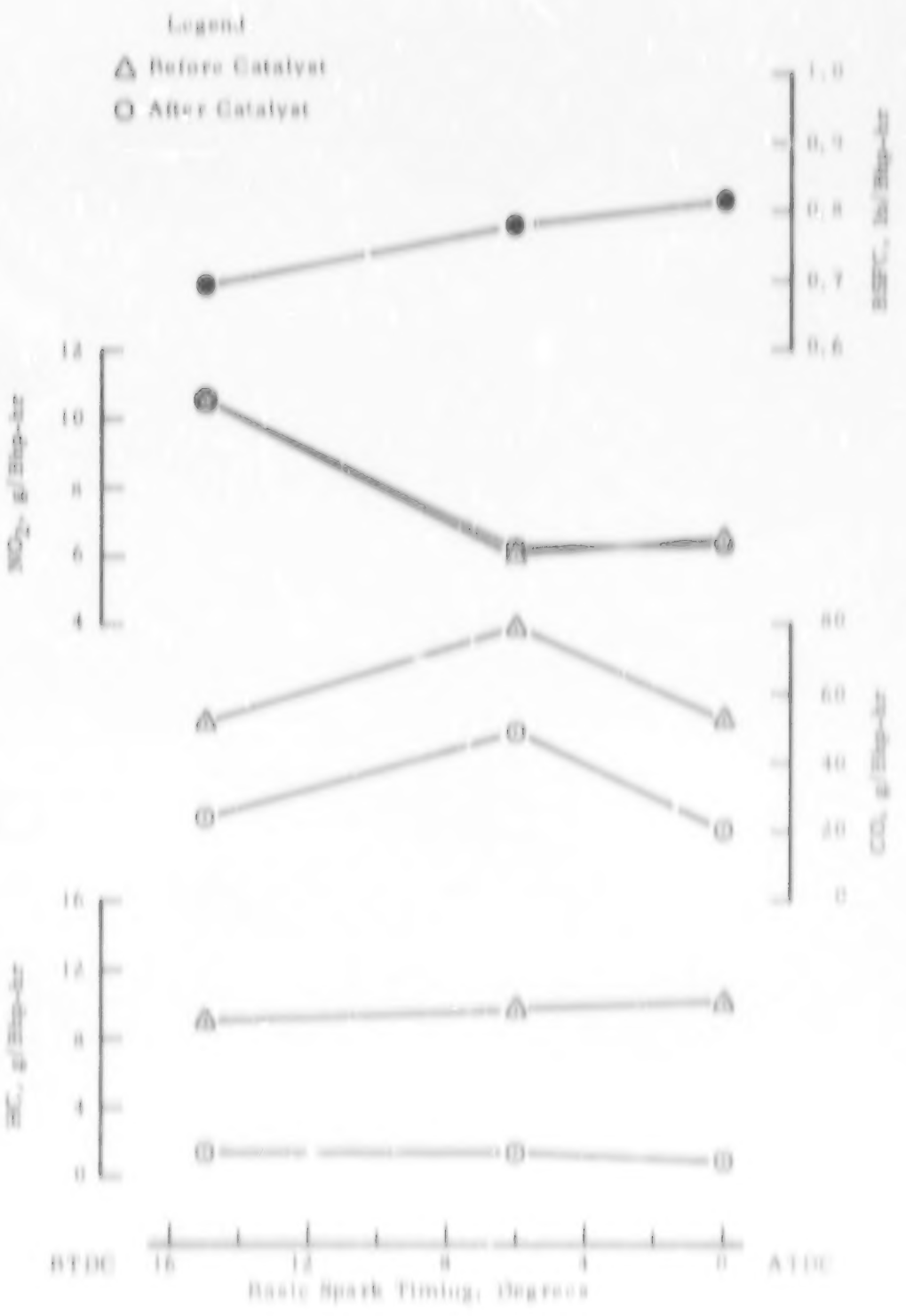


FIGURE 22. EFFECT OF OXIDATION CATALYST ON EMISSIONS WITH SLIGHTLY MODIFIED AIR INJECTION SYSTEM ENGINE 1-3, 23 MODE TEST

TABLE 20. EFFECT OF OXIDATION CATALYST ON EMISSIONS
Engine 1-5, 23-Mode Test

Date	Run	Spark Timing	Sample Point	Grams per bhp-hr HC	CO	NO_x	Weighted BSFC
			Light Duty Air Injection System Intact				
8-24-72	2	6° BTDC	Before Cat.	10.37	98.7	7.48	0.745
8-25-72	1		before Cat	10.48	96.8	6.32	0.752
		AVERAGE		10.42	97.6	6.90	0.749
8-24-72	2	6° BTDC	After Cat.	3.29	61.1	6.78	
8-25-72	1		After Cat.	3.13	59.9	6.63	
		AVERAGE		3.71	60.5	6.70	
			Vacuum Operated Air Injection Distribution Valve Replaced by Simple Pipe "Tee"				
8-25-72	3	TDC	Before Cat.	10.08	52.6	6.45	0.818
			After Cat.	0.98	21.2	6.37	
8-25-72	2	6° BTDC	Before Cat.	9.72	79.7	6.14	0.782
			After Cat.	1.43	49.6	6.22	
8-28-72	1	15° BTDC	before Cat.	9.19	52.1	10.64	0.695
			After Cat.	1.44	24.2	10.59	

TABLE 21. EFFECT OF VARIOUS CONTROL COMBINATIONS ON EMISSIONS
Engine 1-3, 23-Mode Test

Date	Run	Spark Timing	Catalyst	Grams per Bhp-Hr HC	CO	NO_x	Weighted BSFC
0.063 inch (rich) Jets, Modified LD Air Injection, Oxidation Catalyst No EGR							
8/31/72	1	15° BTDC	Before	8.68	140.8	4.60	0.759
			After	1.70	83.5	5.27	0.759
8/31/72	2	6° BTDC	Before	10.91	211.3	3.97	0.853
			After	2.14	156.6	3.28	0.853
0.056 inch (St'd) Jets, Modified LD Air Injection, Oxidation Catalyst Cold EGR Per Schedule A Rate							
8/28/72	2	6° BTDC	Before	11.73	105.3	2.50	0.855
			After	1.13	63.8	2.41	0.855
0.056 inch (St'd) Jets, Modified LD Air Injection, Oxidation Catalyst Hot EGR Per Schedule A Rate							
8/30/72	1	TDC	Before	13.49	174.2	1.60	0.993
			After	2.11	134.3	1.63	0.993
8/29/72	1	6° BTDC	Before	12.72	149.4	2.51	0.862
			After	1.87	112.2	2.51	0.862
8/30/72	2	15° BTDC	Before	11.51	116.5	2.84	0.766
			After	2.23	73.3	2.94	0.766
0.056 inch (St'd) Jets, Oxidation Catalyst, Hot EGR Per Schedule A Rate, But No Air							
8/31/72	3	6° BTDC	Before	10.40	205.4	2.18	0.852
			After	5.48	169.8	2.09	0.852

high, about double the standard or unmodified engine, and the BSFC is also increased.

The results of another combination tried is also shown on Table 21 for the system. Here the engine was operated with standard 0.056 inch jets, the modified light-duty air injection system and with EGR on a cold and hot basis. The EGR schedule used was Schedule A from Table 18. Schedule A was designed to give the maximum rate of EGR and the maximum NO_x reduction without serious engine problems. The exhaust was first recirculated through the heat exchanger with the very low NO_x values resulting per the 8-28-72 runs. CO was not particularly better than unmodified and this caused great concern over this approach. The catalyst was apparently unable to overcome the increased CO by the Schedule A EGR rate.

To study the Schedule A under the more conventional approach of recirculating the exhaust with little or no cooling, i.e. internal EGR as with light-duty gasoline engines, the piping was close connected between the engine's exhaust and the reentry plate located below the carburetor. It may be helpful to look back at the Figure 17 photographs that show only a control valve and thin plate orifice with thermocouple for gas temperature measurement in a relatively short length of pipe. To manually operate the valve, the mass flow of the EGR was instantly computed and compared to the mass flow of air into the engine. The rate was then adjusted as closely as possible to that given for Schedule A in Table 18 and determined on a mass basis.

The results are summarized on the bottom half of Table 21 and are for the engine with standard jets, modified air injection, oxidation catalyst and hot EGR according to rate Schedule A. Three spark timings were run to determine this effect. Basically the same effect on emissions with this combination was found as with cold EGR, namely very low NO_x, high CO and low HC.

Figure 23 shows the before and after catalyst 23-mode results for hot EGR (Schedule A) versus the three timing settings studied, TDC, 6° BTDC (standard) and 15° BTDC. Although 15° BTDC timing looks best, it was decided that this combination had to be improved upon because essentially no reduction in CO was obtained. As with Figure 22, the cycle weighted BSFC increased as basic spark timing was retarded.

Before stopping this series of tests, a run was made to simulate operation with the air pump inoperative as with a broken belt. The results of this run are listed on the bottom of Table 21 and may be compared to Run 1 on 8-29-72 when the air pump was operative. Note the great need for air to oxidize the HC and CO in this test configuration. For more data of a detailed nature, please refer to Appendix V for all the tests summarized

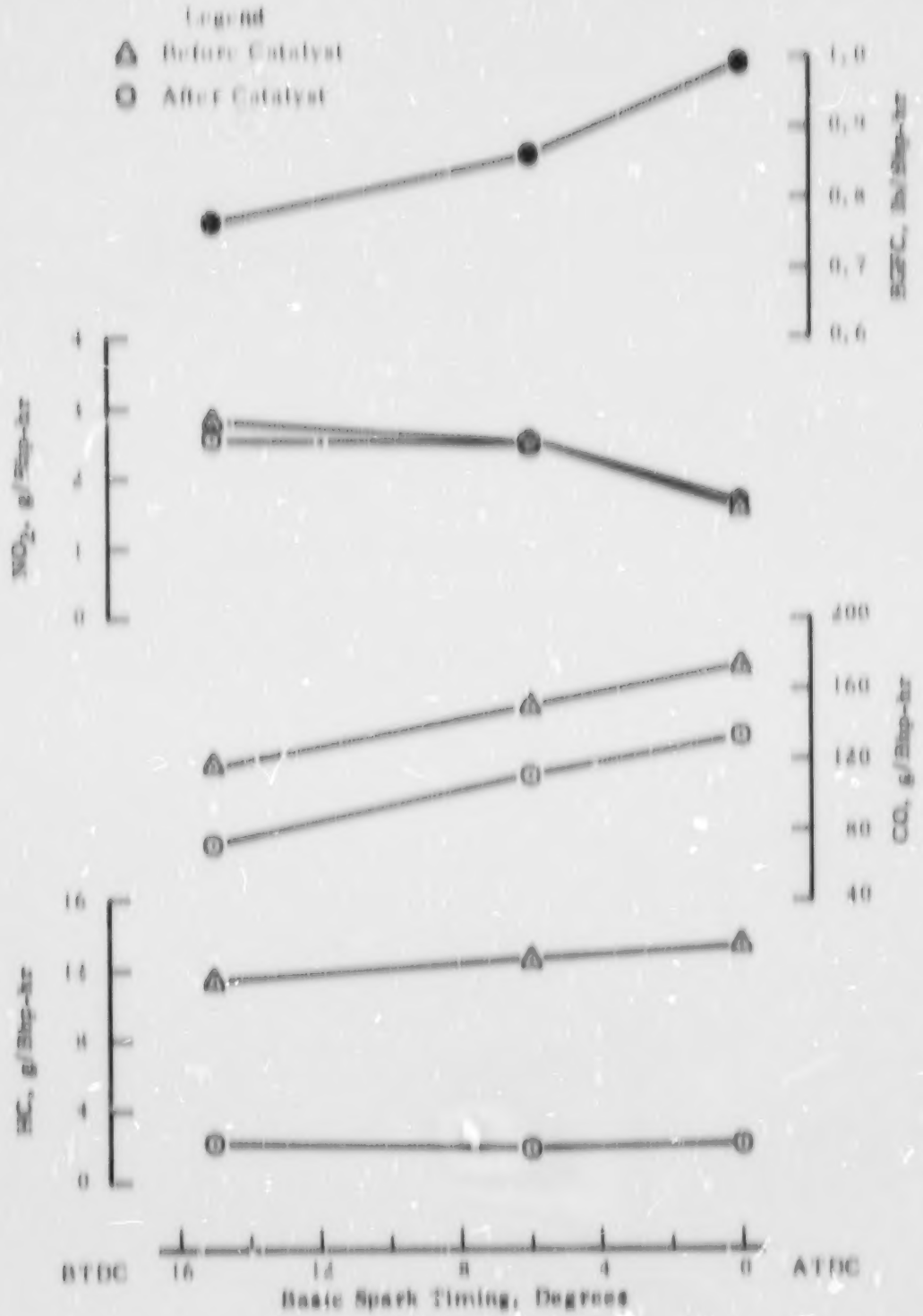


FIGURE 43. EFFECT OF COMBINATION OF HOT EGR (BCH A), OXIDATION CATALYST, MODIFIED AIR INJECTION ON EMISSIONS ENGINE 1-3, 23 MODE TEST

on Table 21. The series of tests with hot EGR versus timing made on 8-29-72 and 8-30-72, are graphed in Appendix V also.

(g) Step 6a - Effect of Best Combination on Emissions

Clearly, a better overall reduction was needed than was found with hot EGR rate Schedule A. Engine 1-3 is extremely sensitive to CO because of a number of factors, one of which is the carburetor action on approaching and operating at wide open throttle. In trying to develop the best compromise, the maximum or top end power should be preserved as much as possible. In this engine, operation at less than two inches Hg intake manifold depression was disasterous on CO in standard or modified condition. Accordingly, Schedule B tailored the EGR to get out of the high CO modes as quickly as possible and, if need be, take the NO_x penalty.

Using Schedule B, also listed on Table 18, fairly good reductions in all emissions were effected and they are shown on Table 22. First, the catalyst did a good job in lowering HC and CO for the best combination as shown by the average before and after results for the three runs made on 9-5 and 9-6, 1972. The resulting HC, CO, NO_2 and aldehydes may be directly compared to the standard, unmodified engine runs made on September 7 and 8, 1972 shown next.

HC was reduced from 6.52 to 1.31 grams per bhp-hr or 80 percent. CO was reduced from 65.9 to 19.2 grams per bhp-hr or 71 percent. NO_x was reduced from 8.34 to 4.09 grams of NO_2 per bhp-hr or 51 percent. Aliphatic aldehydes were also reduced from 0.278 to 0.131 grams of formaldehyde per bhp-hr for a 53 percent change. Cycle weighted brake specific fuel consumption was increased from 0.738 to 0.851 lbs fuel per bhp-hr or 13 percent increase in fuel consumption. In doing so, the "best combination" control strategy reduced top-end power at 2300 rpm from 108 to 95 hp or 12 percent with no effect on power at 1200 rpm.

The data listed on Table 22 is a summary of the individual run results included in Appendix W. In addition to the before and after catalyst "best combination" tabular results, a series of graphs are included that show the average HC, CO, NO_2 intake vacuum, and fuel rate versus power level for 1200 and 2300 rpm. For clarity only, the "best combination" and standard engine results are graphed. The standard engine results are included in Appendix X.

Listed at the bottom on Table 22 are the results of the runs made on August 16, 1972 with the engine in the standard condition prior to the series of tests with control devices, etc. Note the fairly good agreement between the HC, CO, NO_2, power and BSFC between the beginning and ending tests. This indicates the engine did not change or deteriorate materially during the test period. Recall that engine 1-3 used for control technology was modified from that used for baseline testing in that air

TABLE 48. EFFECT OF "BEST COMBINATION" ON EMISSIONS
Engine 4-3, 23-Mode Test

Date	Run	Catalyst	Grams Per bhp-hour HC	CO	NO_x	Aldr	Weighted BSFC	Max Hp Obs. at 1500	Max Hp Obs. at 2500
0.056 inch Jets (Standard), Modified Light-Duty Air Injection, Standard Timing (6° BTDC), Hot EGR Per Schedule B									
9-5-72	1	Before	11.77	56.9	3.94	---	0.846	50	95
9-6-72	1	Before	11.08	49.1	3.60	---	0.833	52	95
9-6-72	2	Before	10.89	44.3	4.40	---	0.813	52	95
AVERAGE			11.25	50.1	3.98		0.831	51	95
9-5-72	1	After	1.19	23.1	4.03	0.130	0.846	50	95
9-6-72	1	After	1.34	18.4	3.70	0.135	0.853	52	95
9-6-72	2	After	1.41	16.1	4.53	0.129	0.813	52	95
AVERAGE			1.31	19.2	4.09	0.131	0.831	51	95
Standard Engine with 0.056 Jets and 6° BTDC Timing									
9-7-72	1	None	8.14	70.9	8.27	0.285	0.740	52	108
9-7-72	2	None	9.01	67.2	8.32	0.283	0.736	52	108
9-8-72	3	None	8.41	59.6	8.43	0.265	0.738	52	108
AVERAGE			8.52	65.9	8.34	0.278	0.738	52	108
Previously Run Standard Engine with 0.056 Jets and 6° BTDC Timing									
8-16-72	2	None	9.4	71.3	8.7	---	0.720	53	110
8-16-72	3	None	8.9	72.8	8.7	---	0.717	53	110
AVERAGE			9.3	72.1	8.7		0.719	53	110

injection cylinder heads and other changes were incorporated.

It was also important to assess the "best combination" control system by the Federal nine-mode test procedure. This was done in a series of tests and expressed in concentration and mass terms on Table 23.

Some fairly respectable reductions in HC, CO and NO concentrations were achieved by the "best combination" relative to the standard engine. HC was reduced from 109.7 ppm to 54.4 ppm n hexane or 50 percent. CO was reduced from 0.44 to 0.06 percent for a 86 percent reduction. NO, corrected, was reduced from 1597 to 614 for a 61 percent improvement. All this was achieved with the standard engine with modified light-duty air injection, an oxidation catalyst, and tailored hot EGR. These levels may be directly compared to the current and proposed Federal limits listed on Table 23.

Only during the higher power modes, the 3 inch and 10 inch intake vacuum levels, was any EGR allowed. The manual control system recirculated 5 percent during the 3 inch conditions and 10 percent of the airflow (mass basis) during the 10 inch mode. All other times, idle, closed throttle, 19 inch and 16 inch, the EGR valve was shut-off.

Table 24 shows a summary of the "best combination" control engine relative to the unmodified engine in terms of grams per bhp-hour using the 1974 Federal Test Procedure calculational method. Note that HC was reduced 48 percent from an average of 3.99 to 2.07 grams per bhp-hour. CO was reduced 85 percent from 24.1 to 3.6 grams per bhp-hour. NO_x was also reduced by 54 percent from 12.92 to 5.92. HC+NO_x was 7.99 with the controlled engine relative to 16.91 grams per bhp-hour with the standard engine. These levels may be compared with the 1973 California and 1974 Federal standards of 40 grams of CO and 16 grams of HC+ NO_x per bhp-hour. Appendix W contains the nine-mode concentration and mass emission results for the engines equipped with the "best combination" of control technology. The results for the two runs made in standard configuration are included as Appendix X. It is interesting to observe the dissimilarity in nine-mode results of engine 1-3 and 2-3. Recall engine 2-3, run with the "best combination" of light-duty air injection, light-duty EGR, oxidation catalyst and standard otherwise was not as effective on the nine-mode test as it was on the 23 mode test. The light-duty EGR valve and its schedule resulted in sufficiently higher HC that could not be reduced by the oxidation catalyst. With engine 1-3, the manual control, laboratory EGR system was not used in those modes of the nine-mode procedure where the reductions in NO_x were outweighed by increases in HC and CO.

Of course, the laboratory EGR with manual control tailored for optimum improvement is nothing more than a laboratory approach, a gadget

TABLE 23. ENGINE 1-3 NINE MODE FTP EMISSION REDUCTIONS (CONCENTRATION BASIS)

Configuration	Date	Runs	Concentrations, Average HC ppm Hex	CO %	NO_x, ppm Corr
"Best-Combination"	9-1-72 9-5-72	3	54.5	0.06	624
Standard	9-8-72	2	109.7	0.44	1597
Current Federal Limit			275	1.5	none
Proposed Federal Limit			160	0.8	2000

TABLE 24. ENGINE 1-3 NINE MODE FTP EMISSION REDUCTIONS (BRAKE SPECIFIC BASIS)

Configuration	Date	Runs	Grams per bhp-hour, average CO	HC	NO_2	HC + NO_2
"Best Combination"	9-1-72 9-5-72	3	3.6	2.07	5.92	7.99
Standard	9-8-72	2	24.1	3.99	12.92	16.91
1973 California and 1974 Federal Limit			40			16
1975 California Limit			25			5

TABLE 33. ENGINE 1-3 NINE MODE FTP EMISSION REDUCTIONS (CONCENTRATION BASIS)

Configuration	Date	Runs	Concentrations, Average HC ppm Hex	CO %	NO_x, ppm Corr
"Best-Combination"	9-1-72 9-5-72	3	54.5	0.06	624
Standard	9-8-72	2	109.7	0.44	1597
Current Federal Limit			275	1.5	none
Proposed Federal Limit			160	0.8	2000

TABLE 34. ENGINE 1-3 NINE MODE FTP EMISSION REDUCTIONS (BRAKE SPECIFIC BASIS)

Configuration	Date	Runs	Grams per bhp-hour, average CO	HC	NO_2	HC + NO_2
"Best Combination"	9-1-72 9-5-72	3	3.6	2.07	5.92	7.99
Standard	9-8-72	2	24.1	3.99	12.92	16.91
1973 California and 1974 Federal Limit			40			16
1975 California Limit			25			9

or means to an end. It demonstrated control possibilities but is, of course, not a proven scheme. No really good idea was obtained about driveability, although the final system could run smoothly in all steady state modes regardless of test schedule. Durability along with driveability for the entire system remains to be demonstrated and, of course, its applicability to engines in general. In defense of the control system, it employed proven oxidation catalysts, light-duty air injection and a fairly simple to automate EGR schedule. No drastic power derating or increase in fuel consumption resulted. The final strategy for both engines 1-3 and 2-3 were almost similar in final design. The only significant difference was in the EGR rate schedule employed. The tailored schedule employed with engine 1-3 was found superior overall for both 23 and nine-mode tests to the light-duty EGR system rates.

Much the same comment regarding advanced or additional control items for study with engine 1-3 can be made as with engine 2-3. The advanced oxidation and oxidation-reduction catalysts, turbochargers, automated EGR valves, fuel injection, etc, were clearly beyond the scope of this project but are not beyond the realm of possibility for effecting even greater reductions than found in this initial project. Such items may effect the same level of control without driveability, fuel and power penalties associated with the currently discussed "best combination". The words "best combination" have always been with quotes because with the fast moving field of emissions technology, this is expected to be short-lived. Another such study is bound to result in a further advance in knowledge and far surpass the performance of the work done so far.

V. SUMMARY AND CONCLUSIONS

The following key points summarize the important findings during this project. Where appropriate, conclusions are presented.

(1) Six 1973 spark-ignited gasoline-fueled engines, three each from two manufacturers, were subjected to a series of baseline exhaust emission tests. The engines included small six cylinder and large V-8 displacement sizes representative of engines popularly used in vehicles rated over 6,000-lb gross vehicle weight. The nine-mode Federal test method, in terms of concentration of hydrocarbons, carbon monoxide, and nitric oxide was performed. The emission results were then converted to mass units of grams of contaminant per bhp-hour using the California ARB procedure for 1973. The latter procedure requires the accurate measurement of flywheel power output and fuel consumption at each mode to permit calculation of brake specific emissions using a carbon balance method.

(2) The six engines were also subjected to an experimental EPA three-speed, multi-load operating schedule which included a much wider variety of operation than the nine-mode procedure. Instrumentation differences must also be accounted for as follows.

> (a) The CL method eliminates the troublesome chemical drier used in non-dispersive infrared (NDIR) analysis of nitric oxide and measures both nitric oxide and nitrogen dioxide. It is compatible with the light-duty regulations. There is one drawback and that is removal of the water of combustion from the exhaust sample. Currently an ice trap, which removes on the order of eleven percent of the NO_2, is used but could be eliminated by preparation of a heated CL. On engines evaluated in this and previous projects, NO_2 in raw gasoline engine exhaust has been less than a few percent.
>
> (b) The heated FID method is considered a vast improvement over the NDIR hydrocarbon analysers used in the Federal nine-mode test. The NDIR method grossly understates exhaust hydrocarbons since they are sensitive to just normal paraffins and an ice trap is employed in the sample system. Although the FID system cannot be considered an absolute or total method, it is substantially better than NDIR and is consistent with the light-duty regulations. There are some slight drawbacks, such as the need for extended purge following a high HC level as occurs during closed throttle operation.

(3) The baseline emissions phase of the project required measurement of oxygenates. The best known method for repetitive samples is the

MBTH method, a wet collected colorimetric procedure that expresses aliphatic aldehydes as formaldehyde. Although the run-to-run repeatability seems satisfactory, the mode-to-mode repeatability was unacceptable. Generally only two of every three demonstrated acceptable ± 20 percent repeatability. The data thus reported must be judged in terms of the method and its precision. Certainly more needs to be done to develop a precise measurement of oxygenates on repetitive samples.

(4) The experimental EPA test method resulted in run-to-run repeatability as good as the nine-mode Federal Test. It is longer and more inclusive and easier to reduce and calculate in terms of a final answer. Precautions must be taken to obtain as accurate power and fuel rate measurements as when measuring exhaust contaminants. Measurement of flywheel power and fuel rate at light loads and lower engine speed is more difficult than at the higher loads and speed.

(5) Engines generally operate on the experimental EPA procedure without problem, although one of the six engines refused to operate at the lower engine speed. The exact selection of engine speeds, power levels, and their respective weighting factors were beyond the scope of this project. These rely on available road data from the operation of vehicles above 6,000-lb GVW. It is difficult to comment on those used in the experimental procedure without substantial additional data.

(6) Two engines, one popular V-8 engine from each group of three, were selected for evaluation of emission control technology. This phase of the study, intended to rely mostly on manufacturer's data and items developed for engines in heavy duty operation, was limited to factory-furnished light-duty items such as air injection (both engines) and EGR (one engine). This was supplemented by SwRI with a commercially-available platinum-type oxidation catalyst reactor and a laboratory manually-controlled EGR system. In addition to a study of these devices, the effect of basic spark timing and carburetor main jet size (air-fuel ratio) was studied. All these were studied singly and in combination to determine emission reduction. The goal was to obtain gross reductions in HC, CO and NO_x without an increase in fuel consumption nor decrease in power available.

(7) Gross reductions with the first engine exhaust emissions were achieved based on the experimental EPA test schedule. Hydrocarbons were reduced by 70 percent, carbon monoxide by 68 percent, oxides of nitrogen were lowered by 30 percent and oxygenates were reduced by 38 percent. Fuel consumption, in terms of weighted brake specific fuel consumption, was increased by 7.4 percent while maximum power was unchanged. Factory light-duty EGR and air injection, standard 1972 engine trim, and basic spark timing were retained. A commercially-available platinum-type oxidation catalyst played a key role in effecting the HC and CO reductions. Driveability and durability aspects have not been specifically determined, though

all the components have been proven in light-duty service. The platinum catalyst depends on lead-free gasoline for operation. Driveability should not be any more affected than light-duty vehicles with the same equipment, though this has yet to be established in a truck.

(8) Operating the first control-equipped engine on the Federal nine-mode procedure failed to give the same degree of emissions control as with the 23-mode EPA procedure. Relative to the experimental procedure, the nine-mode tended to understate the HC and overstate the CO and NO_x. For example, the 70 percent reduction in HC by the 23 mode test may be compared to no change in HC by the nine-mode test. A similar level of reduction in CO by the 23-mode test was found to give about a 90 percent CO reduction by the nine mode. NO_x, reduced 50 percent based on 23-mode data, was reduced by almost 60 percent. The light-duty EGR schedule, creating excessive HC, and the inability of the catalyst to reduce HC during the 19- and 16-inch modes is felt to be the major reason. Had the control-equipped engine been experimented with on the nine-mode schedule, a different combination of control devices would have been used in the 19- and 16-inch intake vacuum modes. From this it may be concluded that the type of test procedure can influence the design and development of an emissions control strategy.

(9) Based on the experimental EPA test procedure, HC was reduced by 85 percent, CO by 71 percent, NO_x by 91 percent and oxygenates by 53 percent with the second engine studied. The engine was operated with standard 1972 trim (carburetor, distributor and basic spark timing), but with light-duty air injection system. The air injection vacuum operation distribution valve was replaced with a simple pipe "Tee" and the same platinum-type commercially-available oxidation catalysts employed. Since no light-duty or heavy-duty EGR system was available from the manufacturer, a manually-controlled laboratory EGR system was employed. An EGR schedule was tailored to minimize NO_x while not seriously affecting HC, CO, power, and fuel consumption. These reductions had penalties in top-end performance at 2300 rpm (13 hp or 12 percent) with no loss in power at 1200 rpm. Weighted brake specific fuel consumption was increased by 13 percent. As with the first engine studied, no assessment of driveability or durability can be given. These were laboratory studies confined to engines operated on stationary dynamometers under constant speed-load engine "mapping"-type conditions.

(10) Operation of the second control-equipped engine on the nine-mode Federal schedule involved re-tailoring the EGR so that five percent was recirculated in the 8-inch mode and ten percent was recirculated in the 10-inch mode. No EGR was used at any other mode and the HC, CO, and NO_x reductions were on the same order of magnitude as obtained on the 23-mode test. The key to this was modifying the EGR schedule specifically for the nine-mode test. The oxidation catalyst seemed to do a better job on HC from this engine than on the first engine. The catalyst supplier

indicated that this was not surprising since the catalyst will preferentially accelerate oxidation of the olefins, aromatics, and certain paraffinic hydrocarbons.

(11) The objectives of the six engine baseline study were achieved and the merits of the experimental test procedure demonstrated. Likewise, the goals of the two engine control technology assessment portion of the project were met in that gross reductions in exhaust emissions were demonstrated. The substantial reductions did not come without a known fuel consumption penalty and an unknown driveability and durability penalty. Only two engines were involved in this limited assessment and much caution must be taken in control technology potentialities of all engines. It is generally true that each manufacturer's engine and even different displacements of a given make will respond differently to emission control strategies. However, limited laboratory demonstration has been made of control potentialities.

VI. RECOMMENDATIONS

This project must be termed a success since substantial reductions in emissions were demonstrated even though limited to three months of laboratory work, two months on one engine and one month on the other.

There were many items uncovered or made known during the last few months that could not be included in this time and fund-limited project. Advanced oxidation catalysts, newly announced oxidation-reduction catalysts, improved exhaust recirculation valves and control modules, turbochargers, to name a few, are still waiting to be considered in depth. And, the hurried nature of the tests conducted under this project could stand some replication and refinement as well as demonstration with additional engine makes and sizes. For example, the light-duty EGR system on one engine reduced NO_x, but more could have been achieved using a schedule tailored for the heavy-duty test procedure.

It is recommended that consideration be given to a long range project to continue research and development on a long term planned basis of control technology for heavy-duty gasoline engines. The intent of such a project would not be to do the manufacturer's job for him, but to demonstrate proof of principle and to evaluate the state of the art. In a way, the effort could act to provide stimulation to the engine manufacturers and those who manufacture control equipment. Those advantages would accrue in addition to the basic objective, namely, determine potential ways to reduce emissions from heavy-duty engines. In closing, the work reported herein represents a good start on what should be a long-range program.

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APPENDIXES

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As requested by the Contract for this project, a total of 100 copies of this report were furnished complete with Appendix data.

This report is complete in itself, however, and does not require the Appendix Data for understanding.